Fall 2018

Portable Fitness Device - Manual Treadmill

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MEMS 411: Mechanical Engineering Design Project

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1 Introduction

In order to help combat the harmful health effects of sitting for extended periods of time, our group will create a portable treadmill. This treadmill's ease of portability will be due to both the lightweight design and ability to decrease its footprint when not in use. The primary demographic for this device will be working professionals who currently spend most of their day in an office chair, thereby giving them the option to walk at a comfortable pace while working. Other demographics include students at all levels to use in the classroom or the library, citizens watching television in their living rooms, and elderly persons who do not want to leave the comfort of their homes to exercise.

2 Problem Understanding

To better understand the problems before us our team completed a detailed background information search, interviewed the customer, and identified key components to the design of our model. The background information study consisted of finding similar designs to our proposed device, related patents, and standards that may prove relevant to our device design and/or device testing. We have also identified the customer needs and the target specifications our prototype should meet by the end of development.

2.1 Background Information Study

An intensive search was conducted to compare this device with others that are currently on the market. There are currently treadmills that serve the general purpose of being portable due to their lightweight design, but these lack the ability to decrease the walking surface. Related patents and relevant standards are included as well.

2.1.1 Similar Designs

One device that serves a similar purpose to ours is the Titan Fitness Under Desk Walking Treadmill seen in Fig. 1. Unlike our device, this does not have the capability to change size when transporting and weighs 114 lbs, a considerable amount for many people to carry. It is designed to fit under a standing desk, provides a small console that controls the speed of the treadmill, shows expected walking metrics, and is connected to a safety key to stop the treadmill if disconnected. It operates at speeds between 0-4 mph in 1/2 mph increments and is not able to change its level of incline. The treadmill has a total length of 65", total width of 25", and max height of 8". The belt itself is 53" long and 18" wide. It has an electrically powered motor, is rated for a max user weight of 250 lbs, and is available for $479.

Figure 1: Titan Fitness Under Desk Treadmill featuring a console and a walking surface area 53" long and 18" wide.

A second device is the ProGear 190 Manual Treadmill seen in Fig. 2. This model can fold up, consists of a steel frame, and weighs just 49 lbs, making it relatively easy to transport. The electronic display on the rail allows the user to see their walking metrics and is powered via battery. The user can set the level of incline to be 6° or 10° to suit their needs. The treadmill is 47" long, 23" wide, and 51" tall. The belt itself is 43" long and 13.25" wide. The max user weight is rated for 230 lbs and it is available for $130.

(a) ProGear Manual Treadmill at a 10° incline.

(b) ProGear Manual Treadmill folded and being transported.

(c) ProGear Manual Treadmill electronic display.

Figure 2: ProGear Manual Treadmill featuring an electronic display and walking surface area 43" long and 13.25" wide.

A third device is the Exerpeutic 100XL High Capacity Magnetic Resistance Manual Treadmill seen in Fig. 3. It is very similar to the ProGear 190 treadmill in appearance but is made more durable for larger users, pushing the total weight up to 73 lbs. It has a larger computer display and has three incline levels of 8°, 10°, and 15°. It has two flywheels with an extended belt and offers 8 levels of magnetic tension to help stabilize the speed of the belt at any setting. The treadmill is 50" long, 29" wide, and 50" tall. The belt itself is 45" long and 16" wide. The max user weight is rated for 325 lbs and it is available for $290.

(a) Exerpeutic Manual Treadmill at an 8° incline.

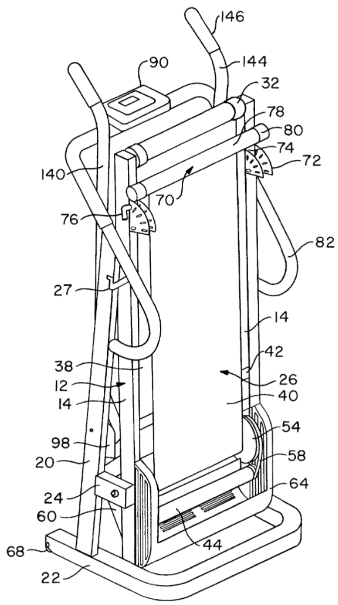
(b) Exerpeutic Manual Treadmill folded and being transported.

(c) Exerpeutic Manual Treadmill electronic display.

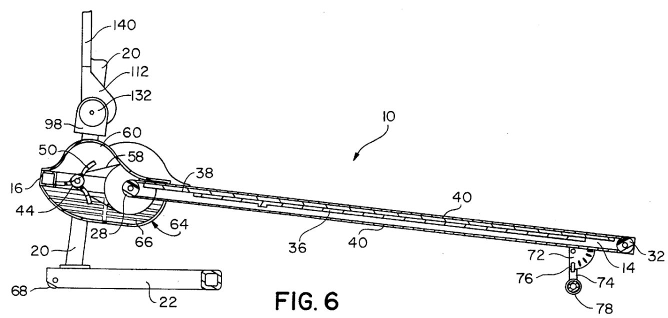
Figure 3: Exerpeutic Manual Treadmill featuring an electronic display and walking surface area 45” long and 16” wide.

2.1.2 Related Patents

One related patent is Patent US5897460A, seen in Fig. 4, for a motorless treadmill that has an adjustable degree of incline and is designed for the belt to be propelled by the user’s legs. The belt is resisted by a retardant assembly so the user can simply slow their walking pace to decrease the speed of the belt and/or safely step off the treadmill. It includes the details of the retardant assembly and how it operates. It is also able to fold up when not in use.



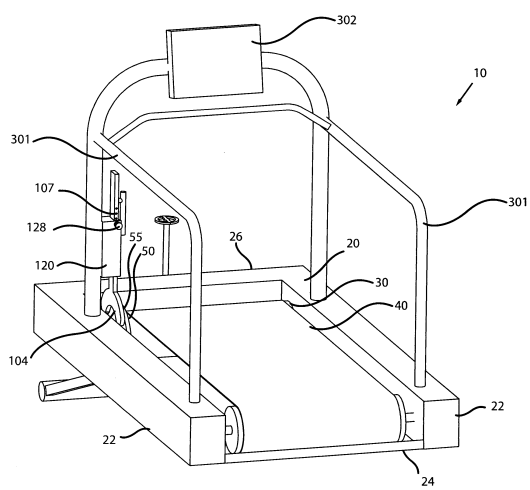
(a) Patent US5897460A when folded.



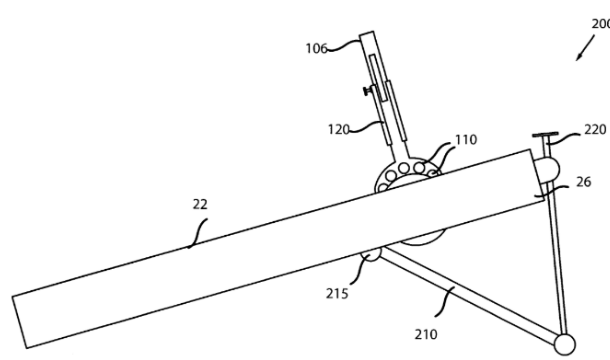
(b) Section view of Patent US5897460 at an incline setting.

Figure 4: Patent US5897460 for a motorless treadmill with views when folded and at an incline.

A second related patent is Patent US20150080189A1, seen in Fig. 5, for a treadmill that has a manually adjustable magnetic resistance system and an adjustable incline angle. The user can change the magnetic resistance to different positions in order to vary the resistance of the rotation of the flywheel. The belt is propelled by the user's legs and the treadmill can be folded when not in use.



(a) Patent US20150080189A1 when in use.



(b) Patent US20150080189A1 side view at the highest incline setting.

Figure 5: Patent US20150080189A1 for a moterless, magnetic resistance treadmill with an in use view and side view when at an incline.

2.1.3 Relevant Codes and Standards

One very relevant standard to our design will be the Standard Specification for Motorized Treadmills ASTM F2115-18. It covers many aspects of treadmills including stability, prevention of injury, and the need for foot rails and handrails. This will make our team ensure all moving parts are sufficiently covered to avoid fingers or shoelaces getting caught in the machine. Also, we will need to determine the feasibility of adding a handrail to an item that could potentially operate while being partially under a desk.

Another standard we will need need to incorporate is the Standard Test Methods for Evaluating Design and Performance Characteristics of Fitness Equipment ASTM F2571-15. This provides methods to evaluate a piece of fitness equipment once it is ready for use to make the piece of equipment as reliably designed as possible and to help reduce injuries due to design deficiencies. Our team will have to keep these test methods in mind so our final product can be tested by well-proven industry standards.

2.2 User Needs

After the team interview with the customer we have summarized the conversation in Table 1. Included in the table are the questions asked, the response by the customer, our team's interpretation of the customer's response, and a rank of importance from 1-5, with 1 being of little importance and 5 being of most importance.

The product our interview was in regards to was a portable treadmill (FD) that can decrease in surface area when not in use. The customer is Muhammad Elahi and the interview was conducted via conference call for about 30 minutes. The interview took place in Urbauer 318 on the Washington University Danforth Campus on September 7, 2018.

Table 1: Customer needs interview questions and interpreted needs.

Question	Customer Statement	Interpreted Need	Imp.
Total weight	Light enough to be easily carried by adult	FD is easy to transport alone	5
How long when in use	Long enough to take a comfortable stride, but not take up excess space	FD is no longer than longest stride	3
How small when not in use	Half of extended area/normal size	FD decreases footprint by half when not in use	5
Manual or powered track	Either, as long as it meets goal of being portable/changing in size	FD power supply does not hinder weight/portability	3
Electric or battery powered	Either, maybe battery similar to hoverboards, reach speeds of 1-3 mph	FD has lightweight power supply	3
Portability Importance	Number one priority	FD has lightweight, compactable frame	5
Core audience	1: Working professionals who sit all day, 2: People who sit on couch and watch TV, Dream: Students in classroom/library	FD can fit in cubicle in use	5
How loud can it be	Quiet enough to take to library and not disturb anybody. Portability is more important than being quiet	FD is quiet	2
How safe for children	Needs to be safe for children to be around	FD is safe	4
Belt surface material	Not sure, up to us and anything is viable	FD belt provides traction can change surface area	5

The interpreted needs were then assigned a 'Need Number' in Table 2 and the importance ranking is again displayed next to the interpreted need.

Table 2: Interpreted customer needs and importance ranking.

Need Number	Need	Importance
1	FD is easy to transport alone	5
2	FD is no longer than longest stride	4
3	FD is half of longest stride when not in use	5
4	FD power supply does not hinder weight/portability	3
5	FD has lightweight power supply	3
6	FD has lightweight, compactable frame and compactable	5
7	FD can fit in cubicle when in use	5
8	FD is quiet	2
9	FD is safe	4
10	FD belt provides traction, can change surface area	5

2.3 Design Metrics

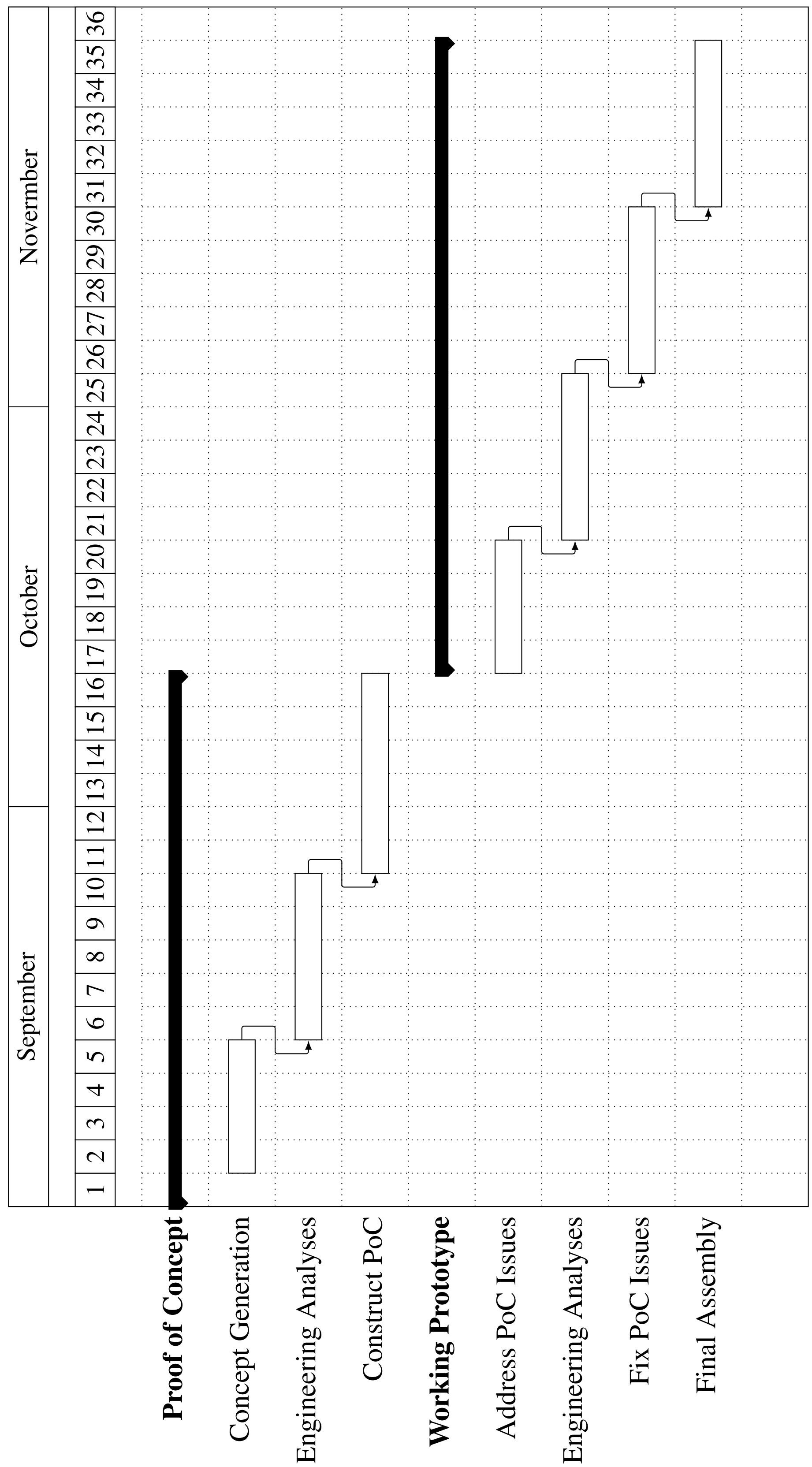
In order to test the qualitative interpreted needs, our team has determined more quantifiable and testable descriptions of each need and summarized them in Table 3.

Table 3: Target specifications of interpreted needs.

Metric Number	Associated Needs	Metric	Units	Acceptable	Ideal
1	1, 4, 6	Total weight	lbs	< 50	< 25
2	2, 7	Total in-use volume	ft^3	< 9	< 5
3	3, 6	Compacted treadmill length	in	< 30	< 20
4	2, 7	In-use track length	in	< 50	< 45
5	1, 4	Low-weight cord/battery	lbs	< 2	< 1
6	5	Energy input requirement	kW	< 1	< 0.5
7	8	In-use sound	dB	< 50	< 40
8	9	Standard for sharpness of equipment edges UL 1439	binary	pass	pass
9	9	Standard for design of fitness equipment in ASTM F2571-15	binary	pass	pass
10	3, 10	Compact belt area is $1/2$ of in-use area	binary	pass	pass

2.4 Gantt Chart

Our group used a Gantt Chart to help plan out steps that would aid in keeping us on schedule to finish the project in the given timeframe.


September
October
Novermber
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36
Proof of Concept
Concept Generation
Engineering Analyses
Construct PoC
Working Prototype
Address PoC Issues
Engineering Analyses
Fix PoC Issues
Final Assembly

3 Concept Generation

To gain further insight regarding the design of the device our team created a mockup of the portable treadmill, allowing us to use materials that were easy to work with and could be easily modified in a short period of time. It was extremely low-tech and was meant to give us a rough understanding of how the concept our team had generated on paper may take form in the physical world.

We were then able to use the knowledge gained from the customer needs and the mockup to create a function tree, breaking down the main idea of the device to more detailed subfunctions. Lastly, we created a morphological chart to demonstrate various ways in which the subfunctions may be realized, leading to sketches of preliminary design possibilities.

3.1 Mockup Prototype

The goal of the mockup was to create something that, while attached between two rollers, could contract to approximately $^1/_2$ of its extended length. We used foam board to create sliders that could extend or contract and duct tape to prevent the sliders from becoming disconnected from the device. The wooden rollers are connected to the sliders by duct tape that has been folded over on itself, allowing the axle to spin freely. The strips of duct tape on the outer wheels is representative of the belt the runner would make direct contact with and it was intentionally not complete so the inner portion of the device could be seen. The device when fully extended is seen in Fig. 6 and is approximately 32" long.

Figure 6: Mockup when fully extended as seen from the side.

When you push the rollers toward each other, the sliders move toward the middle and decrease the length of the device from around 32" to around 22". The device when fully contracted is seen from a side view in Fig. 7.

Figure 7: Mockup when contracted as seen from the side.

It is important to note that the width of the mockup does not change. The device when fully contracted and seen from a front view in Fig. 8 shows the width of the mockup is around 12”.

Figure 8: Mockup when contracted as seen from the front.

The mockup was able to influence our thoughts on the design of the device going forward in a number of ways. We were able to obtain a general idea of how we may control the length of the device with the sliders. Now we must use this general idea and apply it to the rest of the treadmill, most notably the running surface directly underneath the belt of the treadmill. If it is structurally feasible we may also use this concept on the rollers to have the device be able to decrease in width in addition to length.

3.2 Functional Decomposition

As seen in Fig. 9, we have taken the main function of creating a portable treadmill and broke made five subfunctions: stowable, vary speed from 1-3 mph, use at work desk/cubicle, absorb foot impact, portable when not in use.

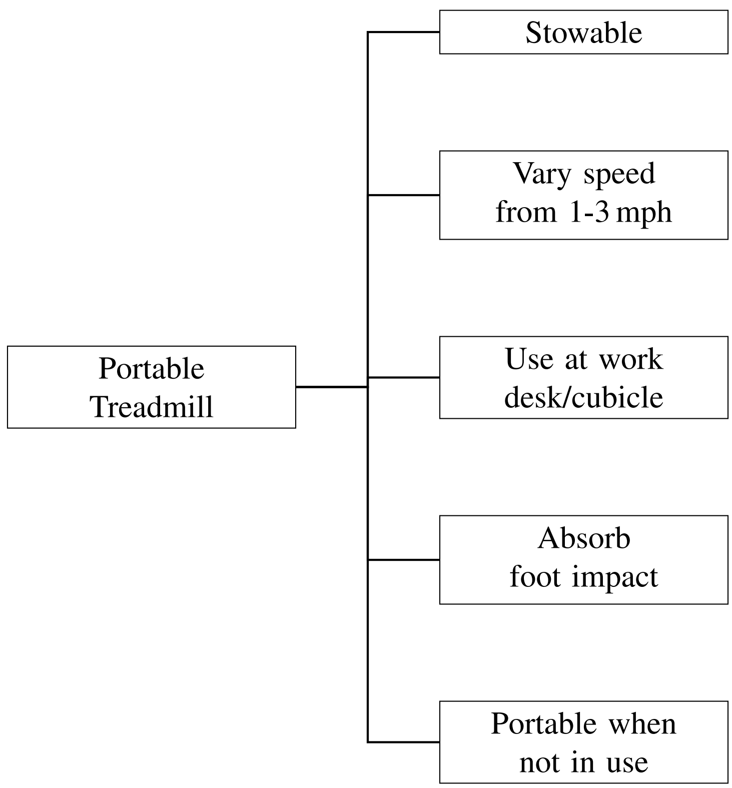


Figure 9: Function tree for our portable treadmill device.

The morphological chart in Fig. 10, where each of the five subfunctions in Fig. 9, was then created to demonstrate a preliminary idea of ways the subfunction could be achieved.

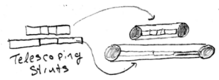
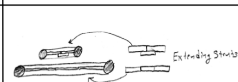
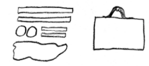
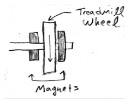
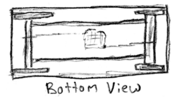
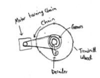
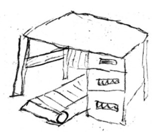
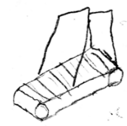
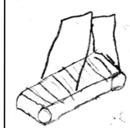
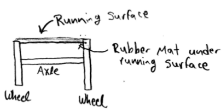
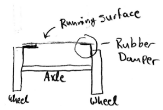
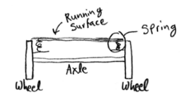
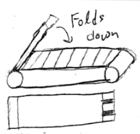
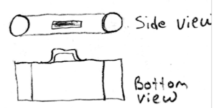
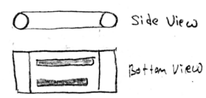
Subfunction	IDEA 1	IDEA 2	IDEA 3
Stowable	 Middle strut slides behind outside struts when stored	 Middle strut slides under outside struts when stored	 Some assembly required
Variable speed from 1-3 MPH	 Magnets on either side of the treadmill wheels to offer resistance	 Controller varies treadmill motor speed	 Derailleur controls gears to change difficulty
Use at work desk/cubicle	 Fits under desk	 Fits in a cubicle with struts to hold while walking	 Fits in a dorm room with struts to hold while walking
Absorb foot impact	 Rubber mat under running surface to reduce impact	 4 rubber dampers by the wheel under running surface reduce impact	 Springs at the wheels reduce foot impact
Portability	 Bar folds down and treadmill has wheels for easy rolling	 Handle on side for easy carrying	 Backpack straps on bottom for carrying

Figure 10: Morphological chart for five subfunctions of the portable treadmill.

3.3 Alternative Design Concepts

Using various ideas from the morphological chart, one design concept was developed by each group member. The designs in Figs. 11-13 were created by Tanner Cooper, David Wolshire and Andrew Bright, respectively.

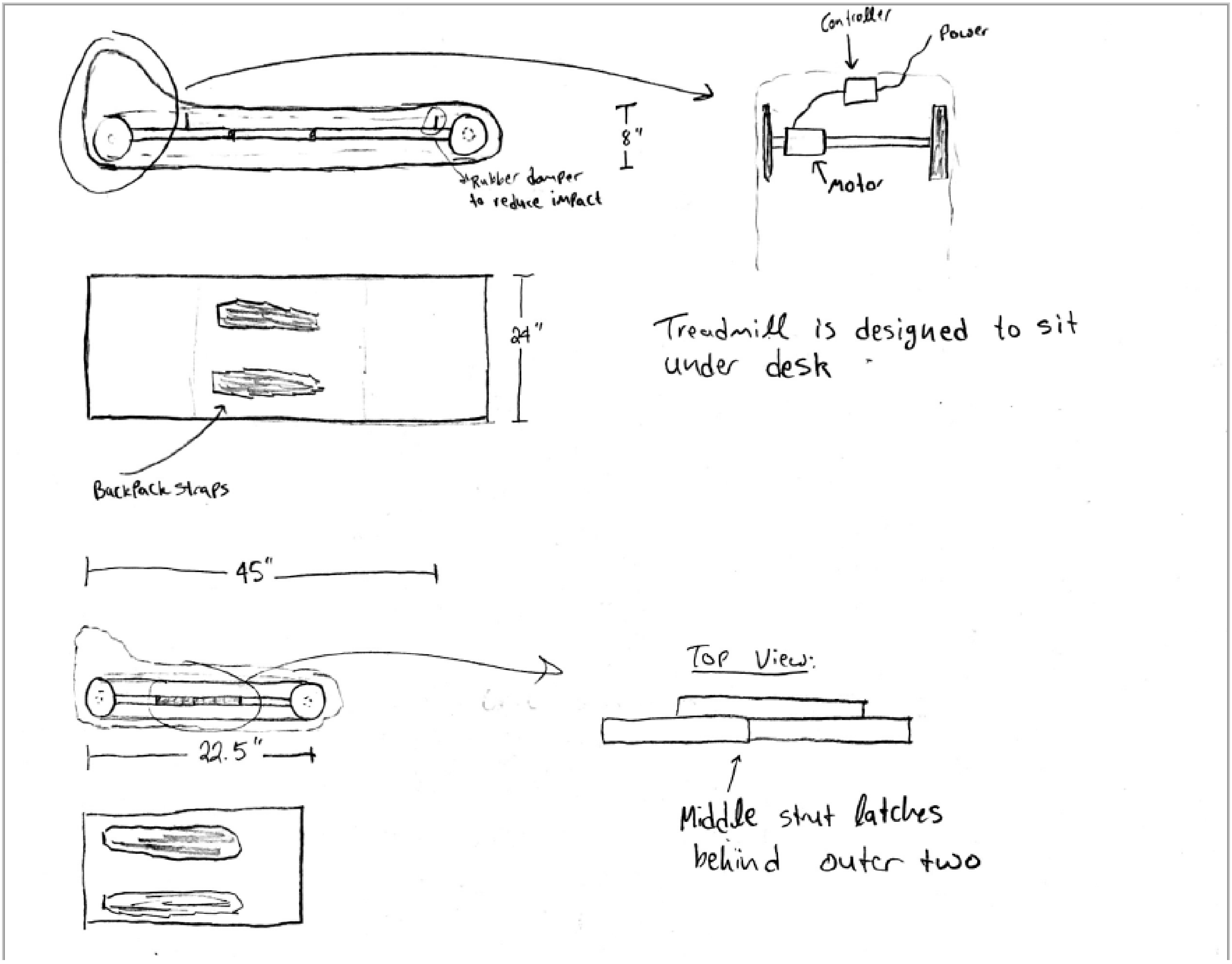


Figure 11: Portable treadmill design concept developed by Tanner Cooper.

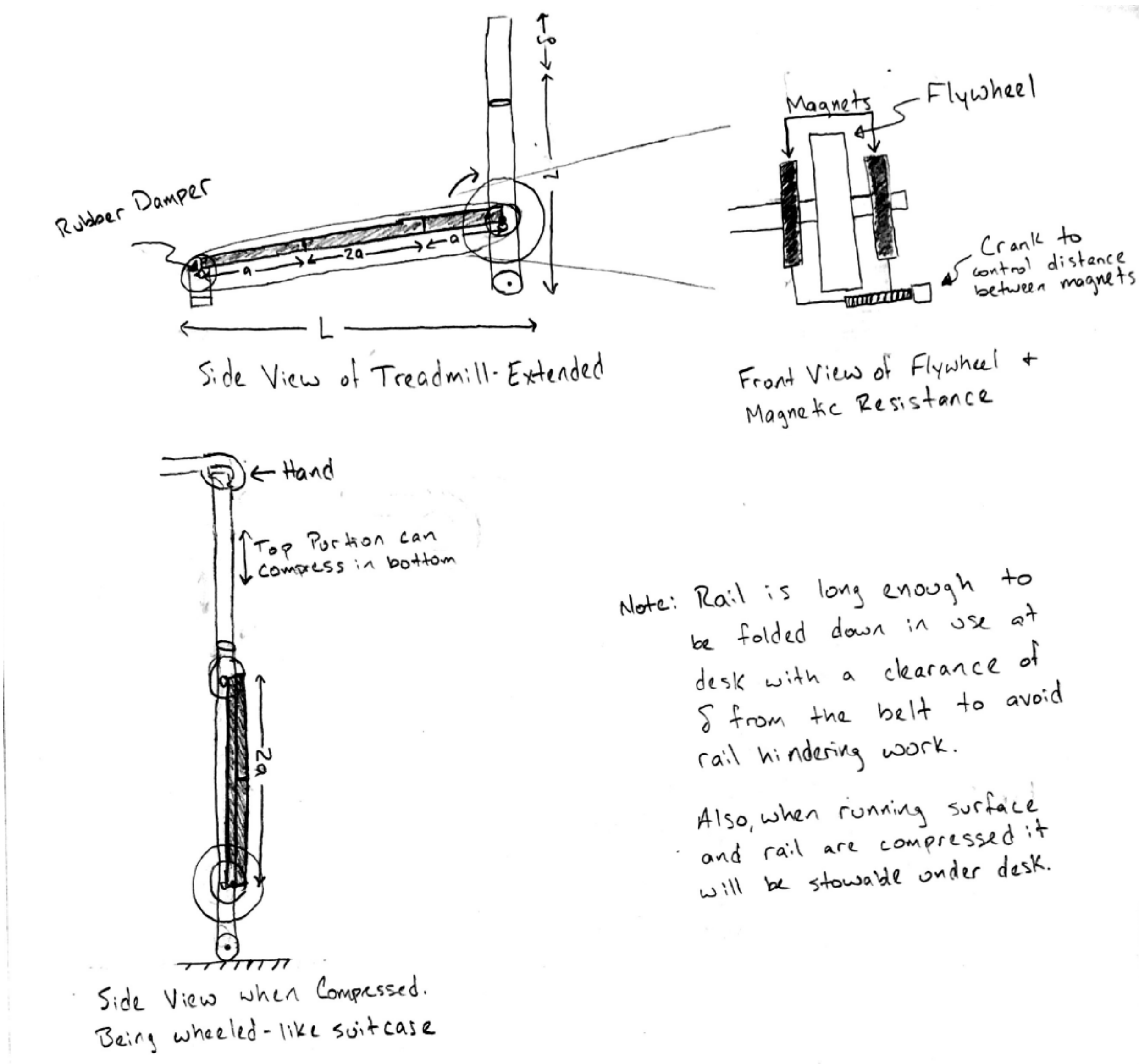


Figure 12: Portable treadmill design concept developed by David Wolshire.

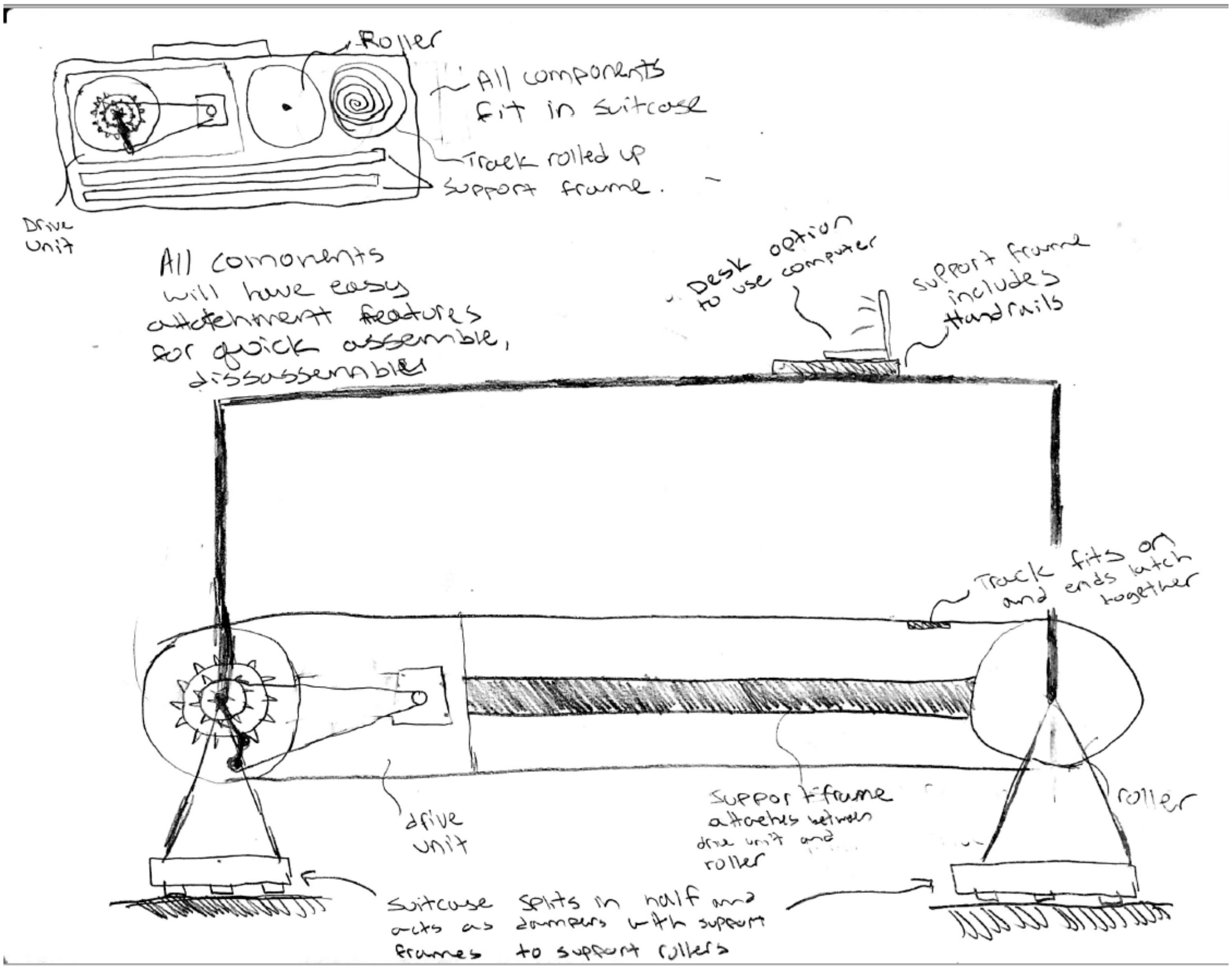


Figure 13: Portable treadmill design concept developed by Andrew Bright.

4 Concept Selection

When developing engineering models to aid in the design of the device, we must determine which models encompass the most of the required needs of the device. We will show the process of the concept selection using an analytical hierarchy, weighted scoring matrix and a detailed evaluation of the results, followed by various engineering models that are meant to aid in making a non-arbitrary decision about important aspects of the device.

4.1 Selection Criteria

A total of six different design criteria were analyzed using an analytic hierarchy process and recorded in Table 4. The table is read as 'The row criterion is ____ than/as the column criterion' with the numerical ratings being: 9 - Extremely more important; 7 - Very strongly more important; 5 - Strongly more important; 3 - Moderately more important; 1 - Equally Important; 1/3 - Moderately less important; 1/5 - Strongly less important; 1/7 - Very strongly less important; 1/9 Extremely less important.

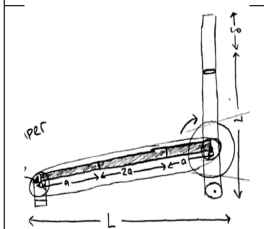
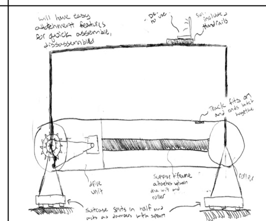
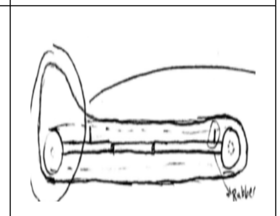
Table 4: Analytic hierarchy matrix for various selection criterion.

	Portable	In-use length	Stowed Length	Weight	Safety	Belt changes SA	**Row Total**	**Weight Value**	**Weight (%)**
Portable	1.00	3.00	1.00	1.00	3.00	3.00	12.00	0.18	18.05
In-use length	0.33	1.00	0.33	0.20	3.00	5.00	9.87	0.15	14.84
Stowed length	1.00	3.00	1.00	0.20	3.00	5.00	13.20	0.20	19.86
Weight	1.00	5.00	5.00	1.00	3.00	7.00	22.00	0.33	33.09
Safety	0.33	0.33	0.33	0.33	1.00	5.00	7.33	0.11	11.03
Belt changes surface area	0.33	0.20	0.20	0.14	0.20	1.00	2.08	0.03	3.12
Total							**66.48**	**1.00**	**100**

4.2 Concept Evaluation

Using the weight percentages found in Table 4, we then produced a weighted scoring matrix to compare the alternative design concepts from Sec. 3.3 to one another. The weighted scoring matrix is shown in Table 5 and the alternative design by David proved to have the highest score.

Table 5: Weighted scoring matrix of the possible alternative designs.

		David		**Andrew**		**Tanner**	
							
Selection Criterion	**Weight (%)**	**Rating**	**Weighted**	**Rating**	**Weighted**	**Rating**	**Weighted**
Portable	18.05	5	0.90	4	0.72	5	0.90
In-use length	14.84	5	0.74	5	0.74	5	0.74
Stowed length	19.86	4	0.79	5	0.99	4	0.79
Weight	33.09	4	1.32	2	0.66	3	0.99
Safety	11.03	3	0.33	4	0.44	3	0.33
Belt changes SA	3.12	1	0.03	1	0.03	1	0.03
	Total Score	**4.125**		**3.591**		**3.000**	
	Rank	**1**		**2**		**3**	

4.3 Evaluation Results

As seen in the weighted scoring matrix, the alternative design concept developed by David had the highest ranking. Therefore, we will proceed in the design process with David's design and will explain its scores for all the selection criteria.

It received a 5 for 'Portable' because it is able to be transported much like a medium sized suitcase, a common item that is designed specifically to be very portable. It received a 5 for 'In-use length' because it is just long enough to be properly used. 'Stowed length' received a 4 because it is able to collapse to half of its in-use length, but it is not able to become as small as Andrew's device. 'Weight' received a 4 rather than a 5 because of the weight of the flywheels and magnets used for resistance. Without handrails or a sturdy base, we believed this makes 'Safety' drop to a 3 at this point, though this will likely increase later in the design process. As of now, we do not have a way for the belt to change surface area and therefore the 'Belt changes SA' criterion scores a 1.

4.4 Engineering Models/Relationships

Seen in Fig. 14 is the running platform of length L directly underneath the belt of the device modeled as a beam with two support forces, R_1 and R_2, on either end and two point forces, each of value P, to represent the feet of the user. One P force is a distance a from one end and the other P force is a distance b from the same end. The shear diagram is shown in the V vs. x plot and the moment diagram is shown in the M vs. x plot. The bending stress σ on the platform is related to the moment of inertia about the neutral axis M, the perpendicular distance to the neutral axis y, and the area moment of inertia I.

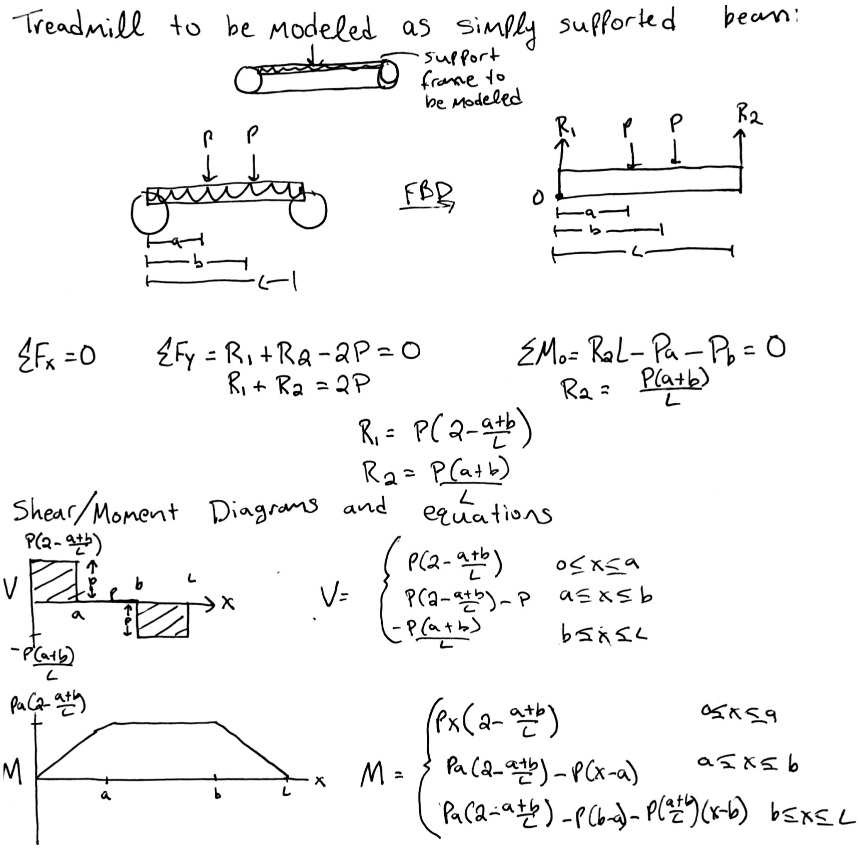


Figure 14: A model of the running platform as a beam with loads.

A model of the torsion experienced in the shaft between the flywheels is shown in Fig. 15. From this, we are able to calculate the maximum normal stress $\sigma_{\max}$ and maximum shear stress $\tau_{\max}$. The equivalent stress, σ_e, takes into consideration the normal stress in the x-direction σ_x, normal stress in the y-direction σ_y, and shear stress between the x- and y-axes τ_{xy}. The goal is to use these relations to adjust our design and optimize the amount of torque in the shaft.

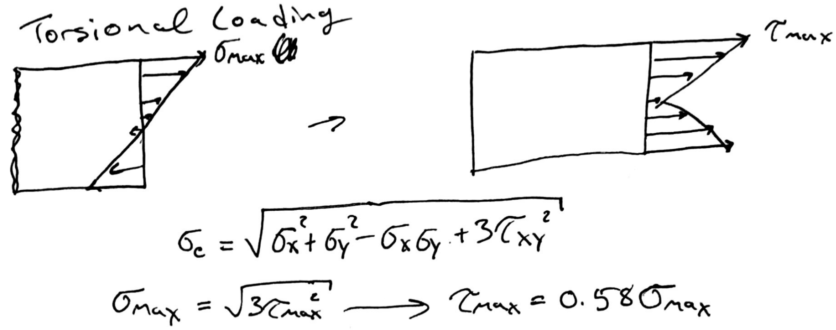


Figure 15: A model of the torsion on the flywheels [1].

The endurance limit, S_n, was found as shown in Fig. 16. We would like to determine the endurance limit for various materials and wheel sizes. This will give us a good idea of what the best material and wheel size combination will make the device safe and durable, leading to a satisfied customer.

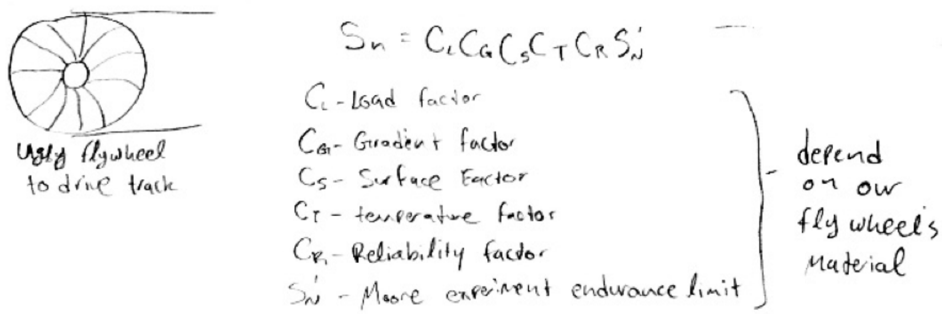


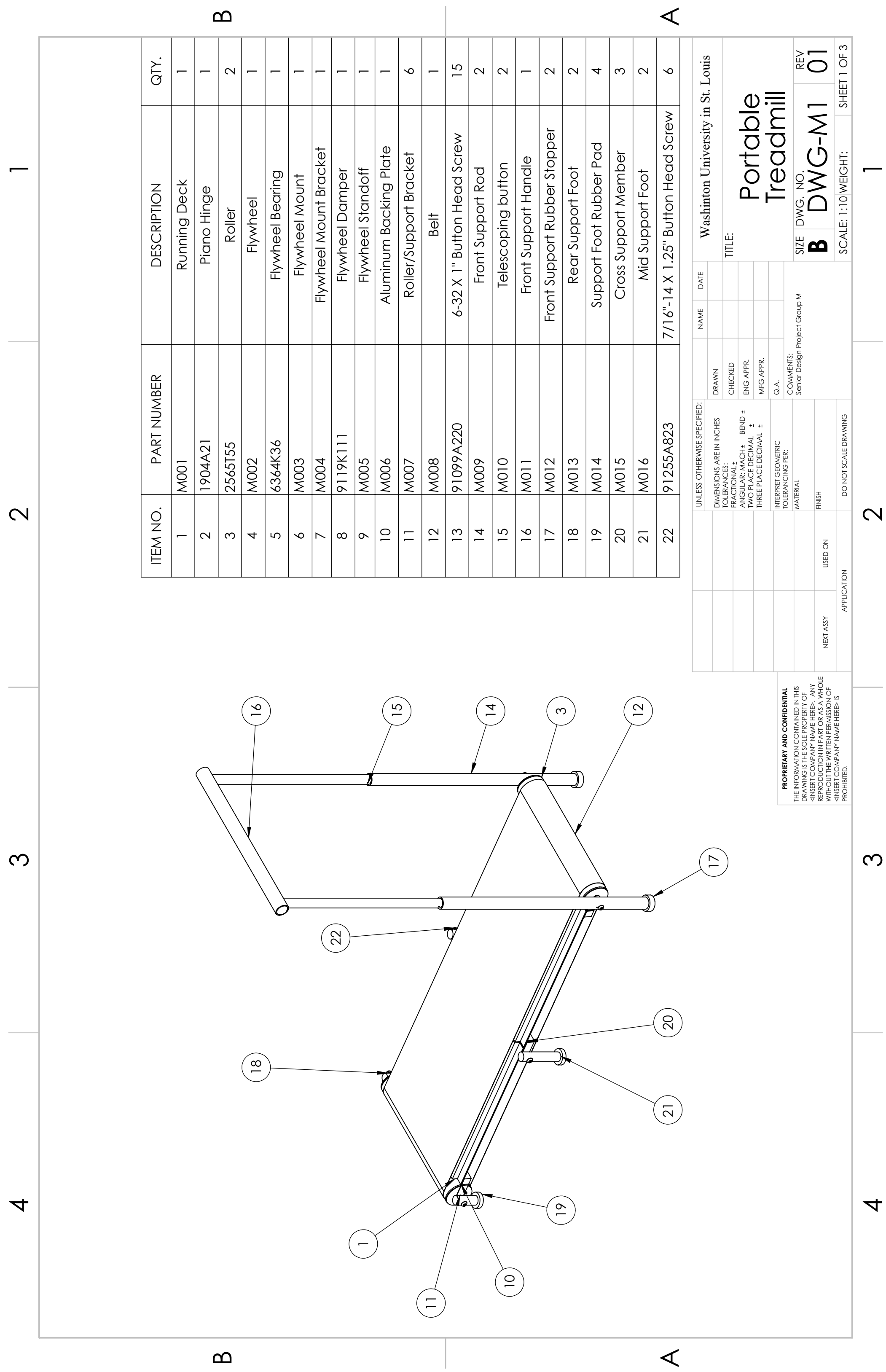
Figure 16: A model of the endurance limit of the flywheels [1].

5 Concept Embodiment

With the aid of SolidWorks, our team developed a CAD model of our design to more efficiently alter components compared to ordering many parts and/or manually machining parts that will not be used going forward. In this section we will show the drawing of these models with an included bill of materials (BOM) and parts list. We will also discuss the main goals our proof of concept should satisfy and the various engineering models used in the decision making of several of the design components.

5.1 Initial Embodiment

The following drawings show the design as it currently stands. Figure 17 shows the assembly view with a bill of materials. Figure 18 shows an exploded view of all components with the numbers on the balloon callouts corresponding to the same part on the assembly view. Figure 3 shows the front, side and top views of the treadmill.



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	M001	Running Deck	1
2	1904A21	Piano Hinge	1
3	2565T55	Roller	2
4	M002	Flywheel	1
5	6364K36	Flywheel Bearing	1
6	M003	Flywheel Mount	1
7	M004	Flywheel Mount Bracket	1
8	9119K111	Flywheel Damper	1
9	M005	Flywheel Standoff	1
10	M006	Aluminum Backing Plate	1
11	M007	Roller/Support Bracket	6
12	M008	Belt	1
13	91099A220	6-32 X 1" Button Head Screw	15
14	M009	Front Support Rod	2
15	M010	Telescoping button	2
16	M011	Front Support Handle	1
17	M012	Front Support Rubber Stopper	2
18	M013	Rear Support Foot	2
19	M014	Support Foot Rubber Pad	4
20	M015	Cross Support Member	3
21	M016	Mid Support Foot	2
22	91255A823	7/16"-14 X 1.25" Button Head Screw	6

Figure 17: Assembly view with bill of materials.

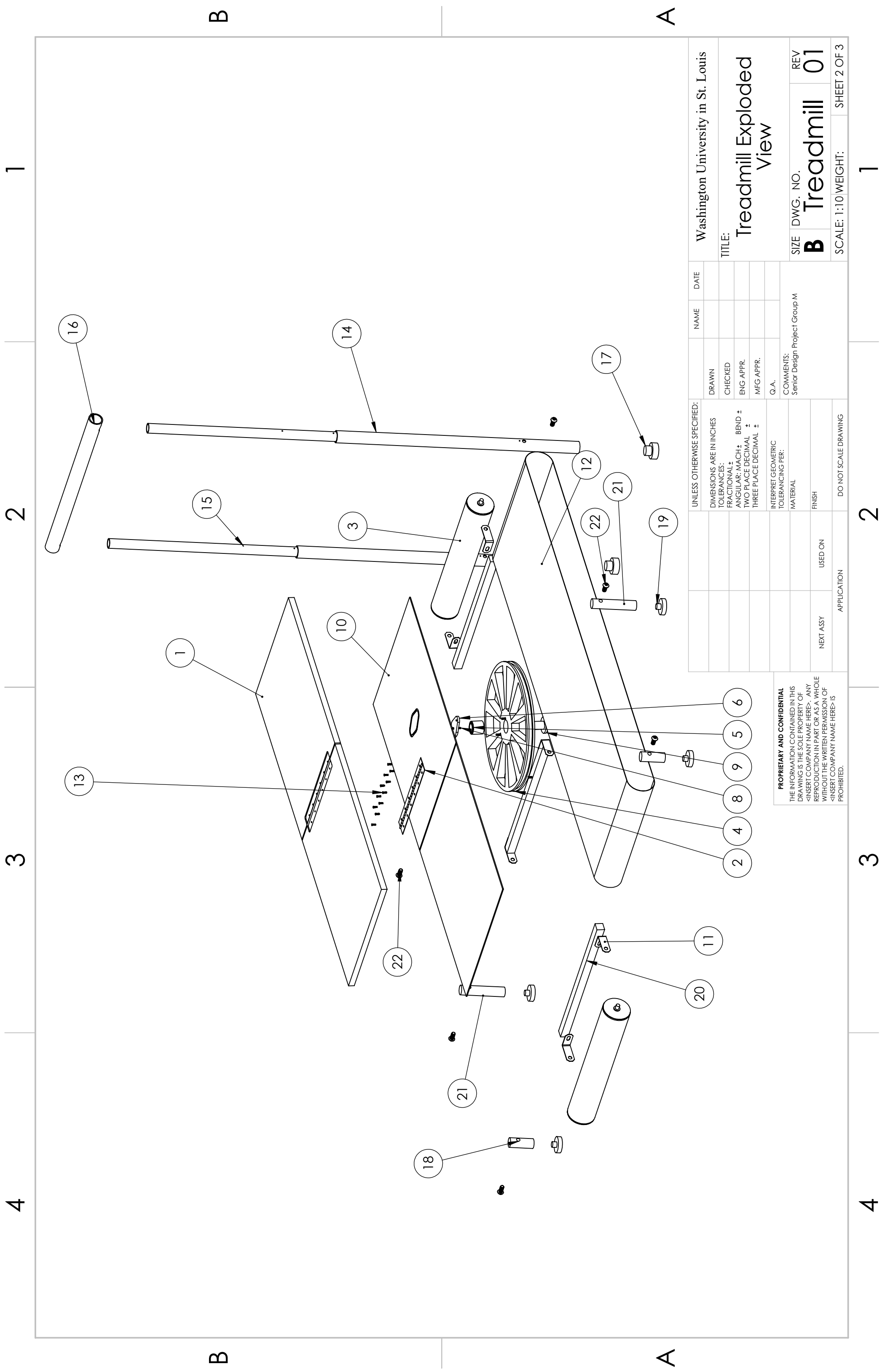


Figure 18: Exploded view with balloon callouts.

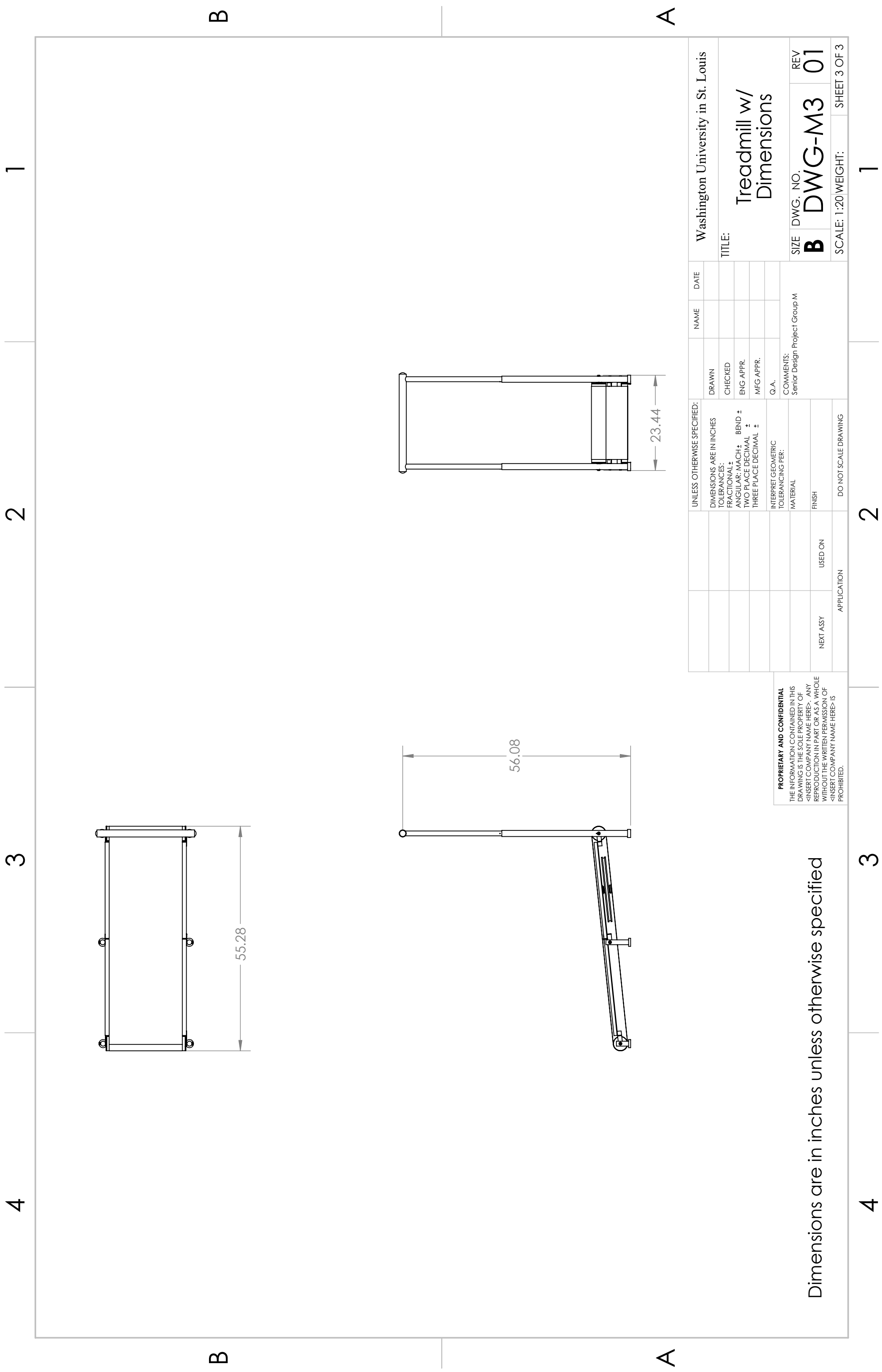


Figure 19: Front, top and side view.

An initial list of parts to be ordered is given in Table 6. Some parts are not listed because they will be easy to find/manufacture materials currently in-house. The total price for all parts is \$441.80. More research on the telescoping tubes will be done to see if we can make them ourselves or find a cheaper alternative since these are roughly half the price of our design.

Table 6: List and estimated cost of potential parts needed for treadmill.

	Part	Source	Supplier Part Number	Color, TPI, other part IDs	Unit Price	Quantity	Total Price
1	Hinge	McMaster	1904a74	0.174” knuckle diameter	\$11.71	1	\$11.71
2	Roller	McMaster	2565t55	Aluminum	\$34.07	2	\$68.14
3	Damper Bearing	McMaster	6364k36	SAE 841 Bronze	\$17.53	1	\$17.53
4	Damper	McMaster	9119k111	6-32 thread	\$2.73	1	\$2.73
5	Screws	McMaster	91099a220	6-32 thread	\$5.58	1	\$5.58
6	Mounting Bracket	McMaster	4960T11	In-House Supply	\$6.76	4	\$27.04
7	Rubber Grips	McMaster	954K124	Black	\$5.00	8	\$40.00
8	Telescoping Tubes	McMaster	4931T63	Steel	\$34.00	6	\$204.00
9	Button Clips	McMaster	92988A650	Galvanized Steel	\$7.66	2	\$15.32
10	MDF	Lowe’s	37461	3/4” thick	\$26.12	1	\$26.12
11	Front Handle	McMaster	9056K84	6061 Aluminum	\$23.63	1	\$23.63

5.2 Proof-of-Concept

Our prototype is meant to satisfy three key goals. Firstly, the footprint of the treadmill when compacted needs to be half of the in-use footprint. Secondly, the entire assembly should weigh less than 45 lbs. Lastly, it must be able to hold a 200 lb person for 5 minutes of walking while at an angle of 8°-10°. The first two goals are to satisfy the portability requirement and the third goal is to prove it is structurally sound for at least a short duration of use.

5.2.1 Design Rationale for Components

Common industry choices for running deck materials are medium density fiberboard (MDF) or a metal. We chose to use MDF due to the large weight difference and the forgiving nature of the material (i.e. the material will ‘give’ when the user’s feet hit the deck without permanently deforming the deck, helping to transfer some of the impact force from the user’s joints for many hours of use).

A $^1/_8$” thick 6061 aluminum sheet is used to connect the roller mounts and the track. With a strength-to-weight ratio of 459 ksi and a density of 0.1 lb/in^3, it provides great support and adds less than 1.5 lbs to the design [3,4]. The hinge that connects the two sections of the running deck was chosen somewhat arbitrarily as we could not find much information about the best hinge type for our load distribution. More research and testing will be done before finalizing this part, but for now we chose a piano hinge because it is one solid piece that spans most of the gap between the MDF boards.

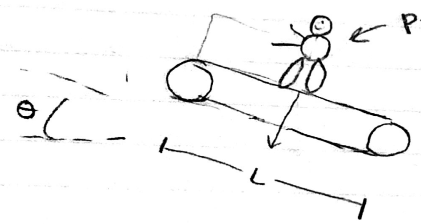
The distance d between the roller axle and the bottom of the rail on the front end had to allow for the angle of the treadmill to fall within the desired range of 8°-10°. The overall length of the treadmill is 55.28” and the length between the center of the rollers is l = 51.78”. Using a desired angle of $\theta = 8°$, simple trigonometry in Eq. 1 can be used to find the necessary difference y on the front end to be

$$y = l \sin\theta = (47.75\,\text{in})\sin(8) = 6.65\text{''}. \tag{1}$$

The thickness of the rubber support adds 0.89" for a desired distance $d = 7.54$".

The thickness of the running deck is rather fixed due to the total weight being of utmost importance. Therefore, we needed to determine the necessary size of a support made of MDF that will be placed near the middle of the treadmill. The two parameters that were variable were the base length b and the height h.

When designing for the maximum bending stress σ our design could withstand, we assumed the worst-case scenario with a person placing all their weight P at the center of the running deck where the hinge is located. Our performance goals account for a 200 lb individual with a worst-case of 240 lb. The angle of incline of the treadmill is $\theta = 8.37°$ and the length of the running deck is 47.8". With $b = 1.2$" and $h = 2.2$", through the analysis shown in Fig. 20 it was determined the maximum bending stress is 39.99 MPa. This is right at the maximum bending stress for MDF of 40.00 MPa, thus its factor of safety is 1.2 [2].



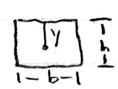
$P_y = P\cos(\theta) = 240\cos(8) = 237.66$ lb

$\theta = 8.37°$

$L_x = L\cos(\theta) = 47.8\cos(8) = 47.33$"

Bending moment $= PL/2 = \dfrac{237.66 \times 47.33}{2} = 5624.899$ lb-in

Bending stress $(\sigma) = -\dfrac{My}{I}$



$b = 1.2$"
$h = 2.2$"

Hinge support cross-section

$I = \dfrac{(1.2)(2.2)^3}{12} = 1.06\ \text{in}^4$

$y = 1.2 \rightarrow \sigma = \dfrac{(5624.899)(1.2)}{1.06} \approx 58$ ksi $\boxed{\approx 39.99\ \text{MPa}}$

Figure 20: Bending moment analysis of the running deck.

For the flywheel there were two key assumptions made. Firstly, our design features spokes and an outer rim, allowing for the removal of unnecessary weight to the device. We considered the flywheel to be significantly thin compared to its diameter, a reasonable assumption when you consider the thickness is 1" and the diameter is 16". With these assumptions the mass moment of inertia is given by Eq. 2, with M being the mass of the flywheel, R being the radius, V being the volume and ρ being the density.

The second assumption is that all the inertia created by the flywheel is equal to the inertia of the front roller of the treadmill due to their coupled nature. The roller is annular (again, to cut weight wherever possible) with an inner radius $r_i = 1.4645$", outer radius $r_o = 1.75$" and a weight of 6 lbs. Its mass moment of inertia is given by Eq. 3.

$$I_{fw} = MR^2 = \rho V R^2 \tag{2}$$

$$I_R = \frac{m(r_0^2 + r_i^2)}{2} \tag{3}$$

Setting these equal to each other and solving for ρ gives the minimum density of the flywheel to allow the treadmill to easily remain in motion. This is seen in Eq. 4 and requires the density of the flywheel to be $\geq 2137\,{}^{\mathrm{kg}}/_{\mathrm{m}^3}$. To give this perspective, the density of aluminum is $\geq 2700\,{}^{\mathrm{kg}}/_{\mathrm{m}^3}$.

$$\rho = \frac{m(r_o^2 + r_i^2)}{2R^2V} = \frac{(0.1865\,\mathrm{slugs})(1.75^2 + 1.465^2)\,\mathrm{in}^2}{2(64\,\mathrm{in}^2)(60.546\,\mathrm{in}^2)} = 0.0024\,{}^{\mathrm{slugs}}/_{\mathrm{in}^3} = 2137\,{}^{\mathrm{kg}}/_{\mathrm{m}^3} \tag{4}$$

5.2.2 Proof of Concept Images

The current proof of concept has a running deck made of MDF, three hinges attaching the two halves of the running deck and supports on the front, middle and back. It does not yet have the rollers or flywheel attached as we are working on finding the proper brackets to attach them to the main body of the treadmill. Figure 21 shows a top view of the proof of concept, Fig. 22 shows a side view of the proof of concept in the in-use position and Fig. 23 shows a side view of the proof of concept when folded. We are working to make the two halves of the deck sit flush with one another when in the folded position. It does satisfy our three performance goals of holding person of 200 lbs for 5 minutes, weighing under 45 lbs (currently $\sim 25 - 30$ lbs) and decreases the footprint in half when folded.

Figure 21: Top view of the proof of concept.

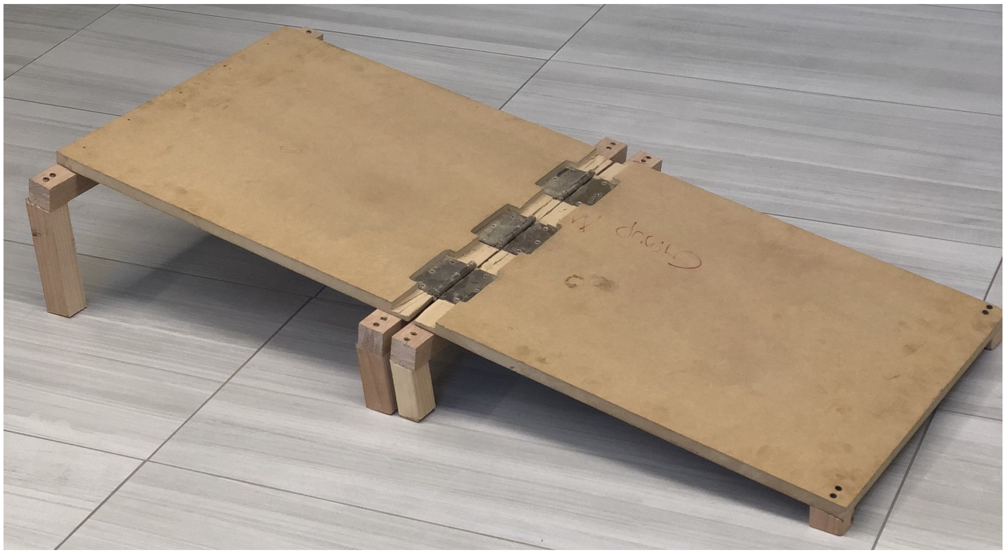


Figure 22: Side view of the proof of concept in the in-use position.

Figure 23: Side view of the proof of concept in the folded position.

6 Working Prototype

Between the proof-of-concept and working prototype there were some design changes and additions added to our treadmill. We will discuss the details of these alterations, show the final prototype, and discuss the results when our prototype was put to the test.

6.1 Overview

An alteration to the hinges in the middle of the running deck was the one key design change that took place between the proof of concept and the working prototype. On the proof-of-concept, the interference of the hinges did not allow for the two halves of the running deck to sit flush with one another when attempting to fold it in half to carry. We therefore attached two hinges together and attached each hinge to a separate half of the running deck, thereby allowing the deck to completely fold in half. A support was also added directly beneath the hinge. The final change made was the addition of the rollers as we were able to find appropriate mounting brackets.

6.2 Demonstration Documentation

Figure 24 shows the prototype in the in-use position. Unfortunately, we were not able to obtain a belt that fit this treadmill in the given time. The length is not a standard belt length, something that was not considered when designing the treadmill.

Figure 24: Prototype at the in-use length.

If you recall from the the proof of concept, Fig. 23 shows the issue we had when trying to fold the running deck in half. The necessary clearance was not available because the hinge knuckles were to sit at the same level of the running deck. As shown in Fig. 25, we therefore attached two hinges to one another for a total of 6 hinges instead of 3.

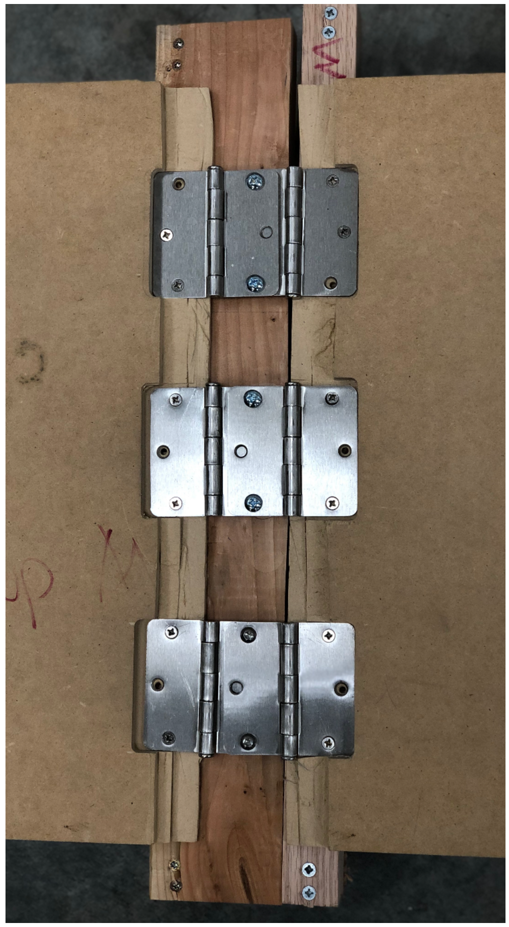


Figure 25: Middle hinge apparatus for the prototype.

Due to the new hinge design, the prototype was able to successfully fold in half and the two halves now sit flush with one another, seen in Fig. 26.

Figure 26: Prototype in the folded position.

6.3 Experimental Results

Recalling our three performance goals, decreasing the footprint when not in use, minimizing weight, and able to be used for 5 minutes, we have essentially met each of them. With the addition of the double-hinge design alteration the treadmill is able to decrease its footprint to exactly half of its in-use footprint. However, this solution is not ideal as there is an increased gap between the halves of the funning deck and another support board had to be placed below the hinges. The general concept could be further explored and there is another concept that could be tried in future testing; a hinge much like that found on a Lenovo laptop and seen in Fig. 27. This is a rather elegant solution that was not thought of until too late in the semester for us to explore it further, but we believe it to be the best solution found thus far.

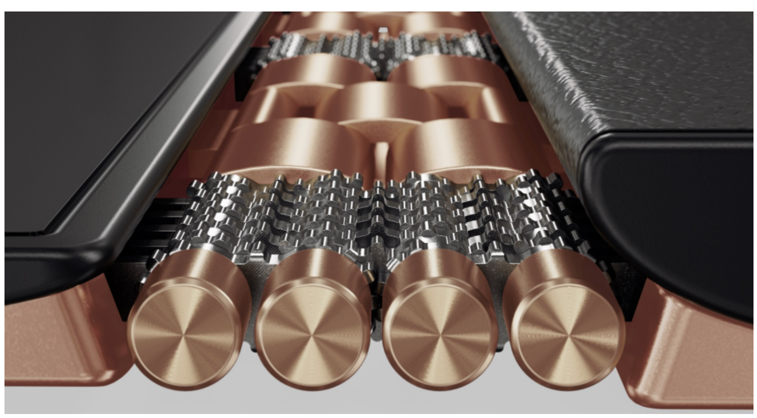


Figure 27: Lenovo laptop hinge.

The second goal was to have the entire assembly weigh less than 45 lbs. It is currently right at the 45 lb mark and there are a number of easy ways this weight can be further reduced. Firstly, the thickness of the running deck can be decreased between ⅛” - ¼” depending on the type of MDF used. Another large contributor to the weight is the rollers at approximately 6 lbs each. The diameter of the rollers can be decreased now that a flywheel is no longer in the design as was originally anticipated and the material can be altered from PVC (which was used out of ease of alteration and due to its low cost).

The third goal was to have a 200 lb person walk on it for at least 5 minutes. This was not exactly tested because we were unable to obtain a belt that fit the current design. We did not take belt dimensions into consideration when building the treadmill and assumed we could find one after the rest of the treadmill was built. As this was not the case, we had a person walk up and down the treadmill for 10 minutes and there were no structural issues. However, the friction between the wooden legs and the concrete floor was not high and there was an occasional movement of the treadmill. With the addition of rubber stoppers on the bottom of the legs the friction should increase enough to minimize the chance of slipping. We therefore believe that if there was more time in the class to purchase and attach the rubber stoppers to the legs, or to order a custom belt or alter the length to fit a more standard dimension that it would be able to be used for the desired length of time.

7 Design Refinement

To better choose the materials used for construction of the prototype there are various engineering aspects to consider. We will conduct an FEM analysis on a key component of our treadmill and discuss aspects relating to design for safety, manufacturing and usability.

7.1 FEM Stress/Deflection Analysis

We completed an FEM analysis in SolidWorks on the galvanized steel bracket that attaches the roller to the running deck. This allowed us to determine if the potential loads experienced by the bracket will cause it to fail or not without risking damage to the equipment or ourselves.

The mesh used during analysis was a medium mesh (between coarse and fine) as seen in Fig. 28. Running the simulation at a finer mesh gave us smaller stress results and the simulation at a coarse mesh is likely to be an inaccurate representation of a realistic load.

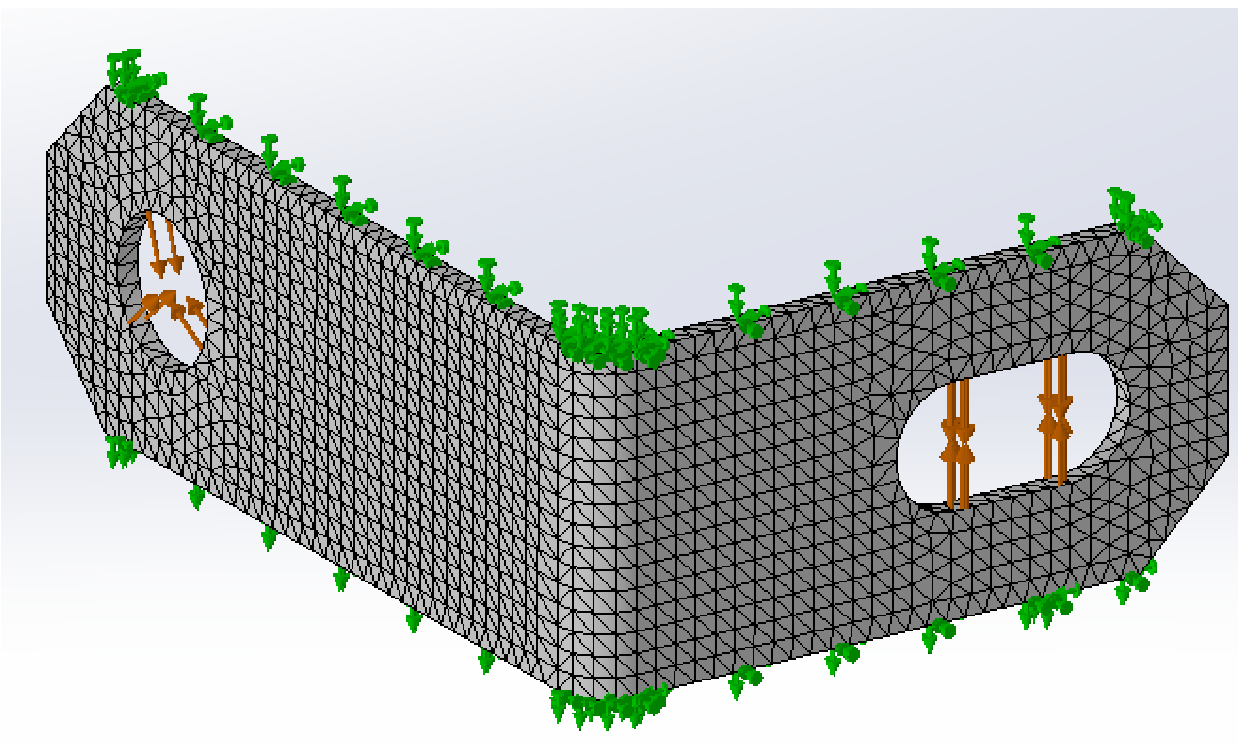


Figure 28: Mesh setup for the galvanized steel bracket connecting the roller and running deck.

A downward force of 900 N (202 lbs) was assumed to be acting on the bolt connected between the running deck and the bracket to account for the worst-case scenario of someone applying the majority of their body weight on a corner of the treadmill. Because the bolt is the only place for the force to be transmitted to the bracket, the largest stress of 54.75 MPa is experienced near the hole for the bolt to go through as seen in Fig. 29. With a yield stress of 203.94 MPa, the factor of safety for the bracket is 3.7 [5]. Note that even though the simulation shows the top and bottom of the hole overlap when under a stress, this is an exaggeration to better visualize where the load has the greatest impact.

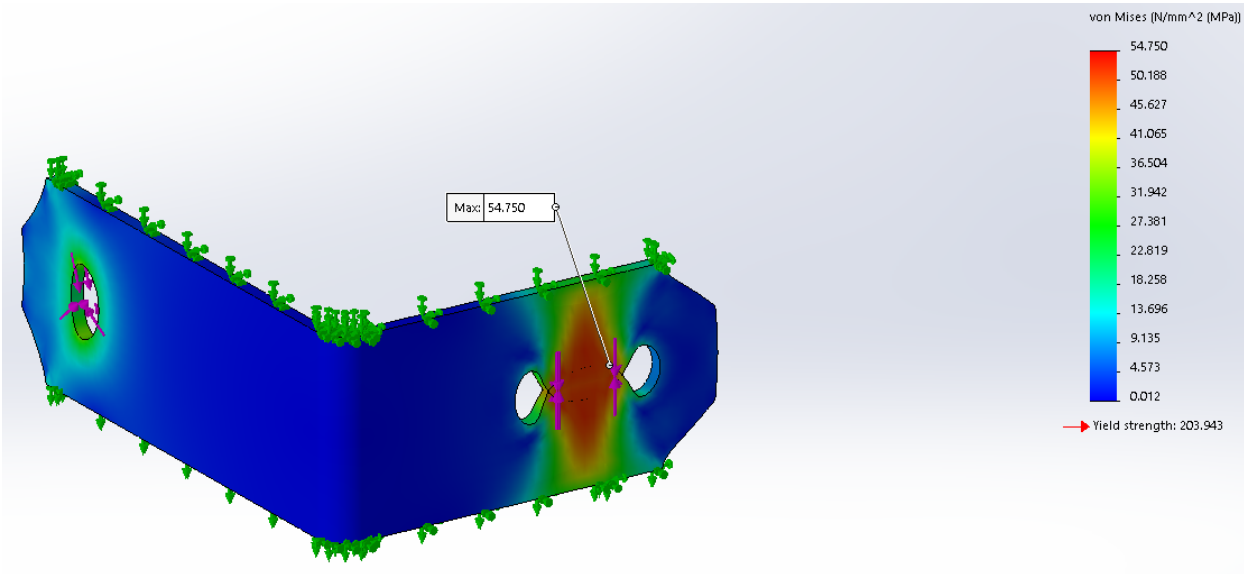


Figure 29: Stress analysis of the galvanized steel bracket connecting the roller and running deck.

As for the boundary conditions, it was constrained on the top and bottom with the assumption that the bolts were tight and secure such that the bracket will not rotate. This is a highly accurate representation of the real-world expected condition as the bracket is attached via fixed bolts in several locations and would only be free to rotate if the bolts were loosened or broke. It was also assumed the entirety of the downward force acts on a single point at the bottom of the bolt hole. Though not entirely accurate as the force would act across the bottom arc of the bolt, it does lead to the highest value for the stress experienced and is therefore a better worst-case condition to design for. These conditions produced the results in Fig. 30 and caused a maximum displacement of 1.935 μm downwards, which is extremely small and is therefore not expected to cause any issues.

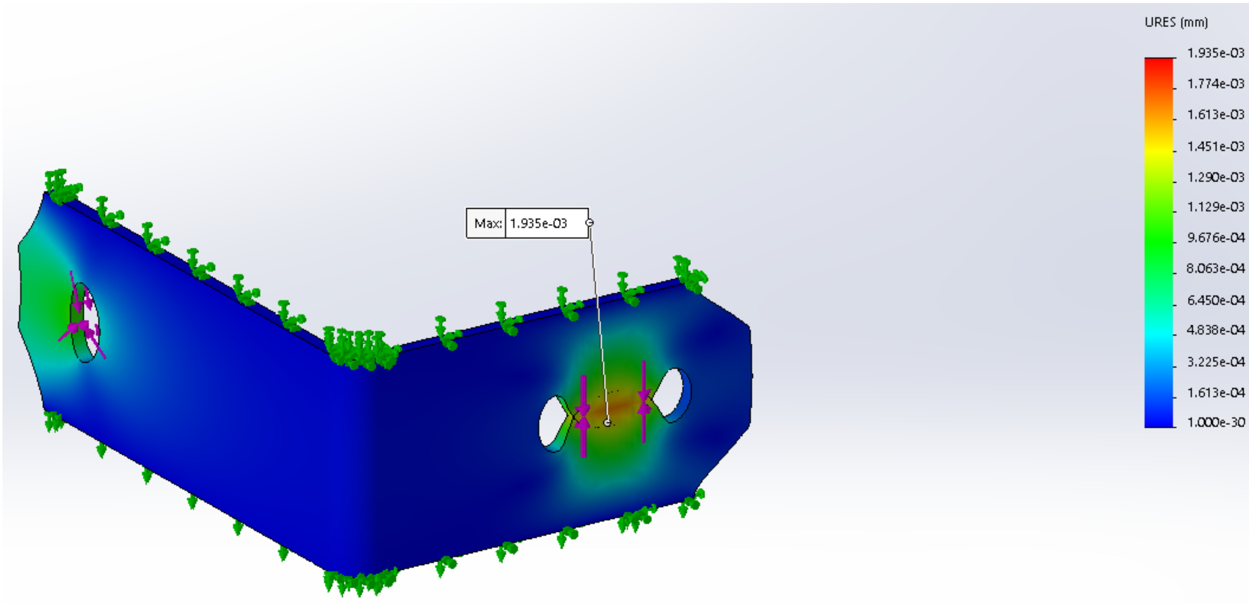


Figure 30: Deflection analysis of the galvanized steel bracket connecting the roller and running deck.

7.2 Design for Safety

The ‘Heat Map’ in Fig. 31 was created to help prioritize potential design hazards relative to each other, displaying the likelihood of a risk to happen and rating the potential impact of the risk. If the risk lands in the red or orange region, it should be addressed immediately to decrease the likelihood of the event occurring, or the device should be redesigned to lessen the impact of such an occurrence. The need to address a risk that lands in the green or yellow area is rather low and should be considered a low priority to address.

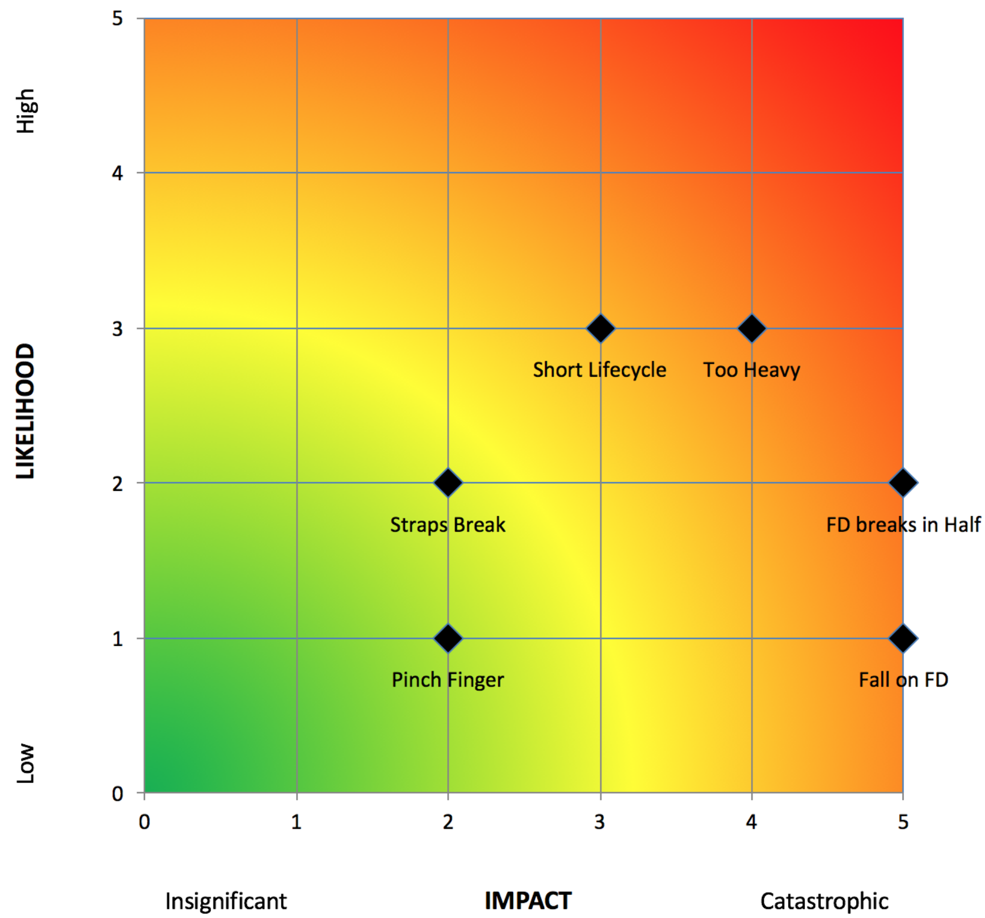


Figure 31: Heat Map prioritizing the potential hazards with the design of the treadmill.

The risk name 'Too Heavy' represents the total weight of the treadmill being too heavy for one person to comfortably carry. This is meant to cover a variety of potential risks including hurting the user's back, dropping the treadmill on the user's foot, etc. The impact of this risk was determined to be a 4 (significant). Anything harming the user is clearly a large impact as it decreases the chances of a positive review, therefore hurting reputation and decreasing sales. It was not considered as catastrophic because it would not make it impossible to use nor would it compromise the performance of the treadmill. It was given a likelihood of 3 (medium) for our prototype because we project it to be between 35-40 pounds and we will not be able to use optimal materials for the scope of this class nor will we have the time to run multiple design iterations to cut weight.

The risk name 'FD breaks in Half' represents the treadmill deck failing at the hinges. A user that is too heavy for the supports or a large and sudden force, such as a jump, directly on the hinges may cause the screws in the hinges to strip out of the holes and leave the treadmill in two pieces. This was given an impact score of 5 (catastrophic) because it breaks the treadmill and has a large potential to severely hurt the user. It was given a likelihood of 2 (low-medium) because the treadmill is currently very sturdy with a load of over 200 lbs and it is meant to be only walked on, making large and excessive forces unlikely.

The risk name 'Fall on FD' represents someone slipping or tripping while using the treadmill.

This could happen if the belt gets liquid on it and becomes slippery, the user trips on their shoe strings or another event control impairment occurs that causes them to fall. This was given an impact score of 5 (catastrophic) because it has a high potential to break the treadmill and seriously injure the user. However, it was given a likelihood of 1 (low) due to experience that one can normally regain their balance at walking speed if the action that causes the loss of balance is minor.

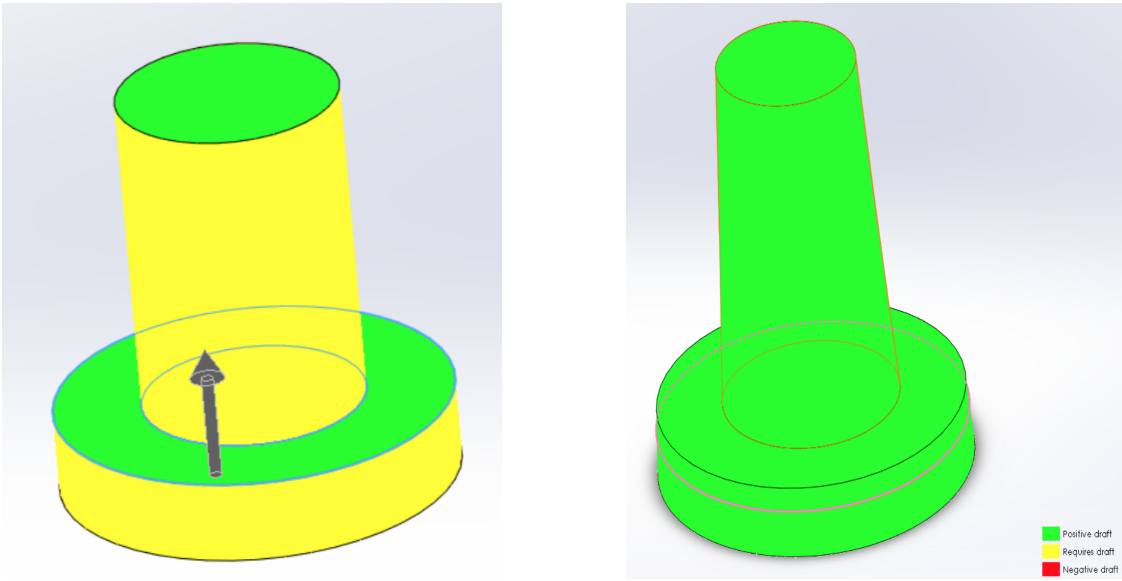
The risk name ‘Short Lifecycle’ represents the treadmill wearing down to a point where use is no longer practical. This can happen if the materials used wear quickly when in contact with one another, there are loose components that warp or shift with use, or it the materials chosen during the design process were not meant to last many uses. This was given an impact score of 3 (medium) because it still allows for use of the treadmill for some time before parts may need to be replaced or repaired and future design iterations could mitigate these problem areas. The likelihood of this occurring in our prototype was given a score of 3 (moderate) due to the limited time frame and budget not allowing more analysis to be done on the optimal materials to use or testing the treadmill for hundreds of hours of use to observe where problem areas in the design may be.

The risk name ‘Straps Break’ represents the straps attached to the treadmill breaking when the user is transporting the treadmill. This could occur if the straps are poorly fastened to the treadmill or the weight of the treadmill is greater than the straps can withstand. This was given an impact score of 2 (mild) because the treadmill is built of durable materials, therefore a small drop should have minimal impact on the performance of the treadmill. It is also unlikely to cause harm to the user except for a potential bruise on their foot. It was given a likelihood score of 2 (low-medium) because the straps chosen are designed to be able to hold a much greater load than our treadmill and they will be attached with strong fasteners.

The risk name ‘Pinch Finger’ represents the user pinching their fingers between the two halves of the treadmill deck when they fold it in half. If the user is distracted or not paying attention their fingers could get caught where the hinges are or have the deck fall on their hand. This was given an impact score of 2 (mild) because, though it may hurt for a few seconds, pinching a finger or having a small weight fall on one’s hand is not likely to cause much of an injury. It was given a likelihood score of 1 (low) because it is difficult to fold with one hand laying on the treadmill deck and nearly impossible to have one’s fingers near the hinges when folding the treadmill.

7.3 Design for Manufacturing

We chose to run a draft analysis on a rubber damper pad that the treadmill rests on. The long tapered section fits into the bottom hole of the support legs (shown in the DFMXpress analysis). The wider section provides a cushion, which acts as a damper, between the support leg and the ground. The part was first made using the extrusion tool in SolidWorks and is shown in Fig. 32a. This type of feature is not good for injection molding since there is no draft angle. Instead, a straight extrusion would need to be made using some sort of turning operation such as a lathe. In order to make the part using injection molding, a draft angle needed to be added. Since this part is meant to be made out of rubber, it is more likely that it would be injection molded than made on a lathe. In order to design the part for injection molding, the loft feature in SolidWorks was used to create drafts by sketching two circles of slightly different diameters, offsetting the circles using reference planes, and creating a loft between the two planes. The important diameter near the base can be maintained while decreasing the diameter of the tip, which is trivial. The final result is shown in Fig. 32b.



(a) DFM analysis before using SolidWorks “Draft Analysis”.

(b) DFM analysis after using SolidWorks “Draft Analysis”

Figure 32: Before and after images of the rubber damper using SolidWorks “Draft Analysis”.

Running the DFMXpress feature in SolidWorks showed the first step in the manufacturing process of a support leg would be to create the through hole on the side, shown in Fig. 33 in a mill drilling operation. The second step would require a turning operation such as that performed on a lathe in order to create a flat-bottomed hole shown in Fig. 34. This blind, flat-bottomed hole cannot be created with a standard twist drill, which would leave a cone-shaped bottom. Since the through hole on the side would need to be made in drilling operation and cannot be made on a lathe, this part would require the use of two different machines; a lathe to create the flat-bottomed hole and a drill to create the through hole running perpendicular to the centerline of the part. If the flat-bottomed hole is made to be a standard drill size, and if it is allowable to have a cone-bottom hole, then the manufacturing cost could be reduced by using a standard drill rather than having to perform a precise turning operation.

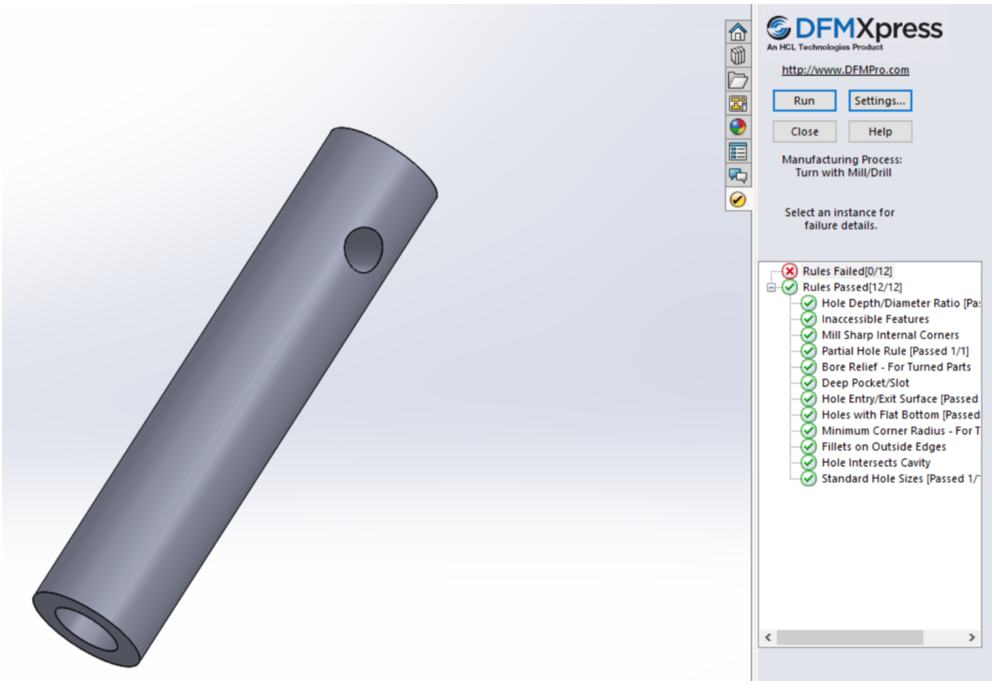


Figure 33: First step in process: turn with mill drill.

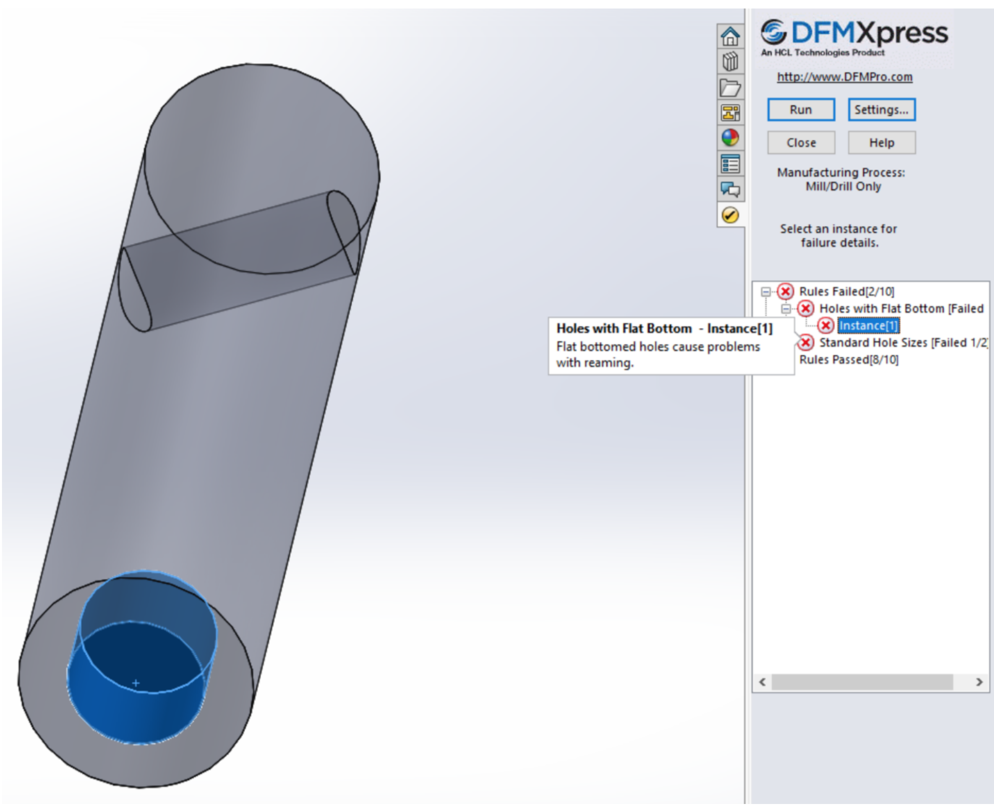


Figure 34: Second step in process: mill and drill only.

7.4 Design for Usability

Several factors not commonly associated with engineering design can have an influence on the usability of a device. Common factors that are taken into consideration are vision, hearing, physical, language and control impairments. For each of these impairments we will discuss the likelihood of their influence on the usability of the treadmill and, when relevant, discuss how the design could mitigate their influence on usability.

Vision: Vision impairments are not likely to influence the usability of our device. There is no user interface to start/stop the treadmill as one just needs to start walking to get the belt to turn. Even if someone has extremely poor vision and possibly suffers from blindness, there will be rails that a user could rest their hands on so they do not drift to the left or right and a cross bar in the front to prevent stepping too far forward.

Hearing: Hearing impairments are also not likely to influence the usability of the device. One does not need to hear to walk on a stationary device. If the device begins to wear down and there is some sort of grinding of parts where there should not be, the only foreseeable issue may be in the user not being able to hear the breaking down of the device before irreplaceable damage.

Physical: Physical impairments are the most prominent impairment that may have an impact on the usability of the treadmill. If someone has one leg it is hard to use it as it was not designed to sustain the load of a person hopping on one foot to keep the belt spinning. If someone has one usable arm there will be a negligible difference in their ability to fold the device or transport it. If someone becomes too fatigued during use the rails should be able to provide support until the belt comes to a stop.

Language: There is no language barrier for our treadmill. There are no necessary instructions for assembly and no interface for the user to control the device in or out of use. There are also no instructions needed on the treadmill itself. Walking is a universal action that does not need to be explained.

Control: It is doubtful the use of our treadmill will be affected by an excessive amount of fatigue. However, if a user is on medication that could cause balance issues or other side effects there could be a higher likelihood of an accident occurring. Any such impairments are unlikely to have a sizable impact on design as they are rare and it is expected the user will have the knowledge of any such conditions before and during use which will mitigate these risks even more.

8 Discussion

There were many facets to this class and project that are worth noting, mainly categorized by the development of the project itself, the available resources for us to use, and the organization of our team.

8.1 Project Development and Evolution

Does the final project result align with its initial project description?

Overall, we do believe our prototype aligns with the original description. It is relatively light especially considering we the suboptimal materials we constructed it with. As for the its ease of being stowed, it is very close to being compact as desired. If the legs were able to detach or fold down it would be rather compact. However, we are missing an element, such as a handle, that makes it easily portable. It is currently a little troublesome to carry long distances.

Was the project more or less difficult than expected?

The project was about as difficult as we expected it to be. It was a relatively simple design considering we chose a manually powered treadmill and did not have to incorporate a motor. All supplies except the belt were easy to find at local hardware stores. The most difficult part of the project was finding a solution to allow it to properly fold in half. No other aspects hindered us much and we did not feel overly pressed to complete it in the given time frame.

On which part(s) of the design process should your group have spent more time? Which parts required less time?

More time could have been spent in the long-term planning before we jumped in on building. We did not think about the belt dimensions as an issue until after we had the rest of the treadmill put together and we ended up needing an uncommon belt dimension, which was not realized until it was too late to order a custom-sized one or make the necessary length changes.

Was there a component of the prototype that was significantly easier or harder to make/assemble than expected?

The rollers were much easier to make and attach than we anticipated. When we were first researching possible rollers to fit on our treadmill, they were all very heavy and we thought we would have to use a lathe to hollow some of it out. However, when we were at the hardware store, we realized we could construct our own rollers by using a PVC pipe, drilling a hole in the end caps, and putting a hollow steel rod through the middle.

In hindsight, was there another design concept that might have been more successful than the chosen concept?

We believe the general concept we chose has the most potential for success. The hinges are a hinderance at the moment, but we believe there to be a few options for a solution in future design iterations. By foregoing a flywheel there are now more options for the hinges, such as placing them on the bottom face of the running deck and allowing it to fold in the opposite direction it currently does. However, this could cause issues with the rollers interfering with each other when folded. There is also the Lenovo laptop hinge design that is worth considering.

8.2 Design Resources

How did your group decide which codes and standards were most relevant? Did they influence your design concepts?

The biggest influence on our choices of codes and standards was from a safety standpoint. One standard discussed the need for handrails to help prevent an injury from falling. Though not incorporated for our prototype, if given more time we would have added handrails for this purpose. Another standard was for testing the performance of the treadmill, which was essentially making sure it performed as advertised and and is stable to help reduce injuries. This did not impact our design concept as it was already planned to be stable and work properly.

Was your group missing any critical information when it generated and evaluated concepts?

The most critical information we were missing was a fundamental lack of understanding hinges. We did not think about how a the hinge does not have the clearance to sit flush with the deck and fold in half on the side of the knuckle (with the single-hinge design). We also thought one middle support on the front half of the running deck could do the trick, but when the user's weight was on the back half the treadmill it would suddenly fall to the floor. Therefore, there were supports put on the front and back halves of the running deck near the hinges.

Were there additional engineering analyses that could have helped guide your design?

One analysis that could have proven useful would have been a SolidWorks stress analysis. This would most likely prove to offer a more accurate result than the simple hand calculations made with some simplifications. Other than the stress analysis, there are not many other analyses we can think would help with the design process as our project was rather simple and had a limited amount of useful analyses that could be conducted.

If you were able to redo the course, what would you have done differently the second time around?

Plan the entire prototype out before moving on from the proof of concept, especially the dimensions. It was very disappointing to our team that we were unable to have an actual working prototype due to not considering standard treadmill belt lengths. I also wish there was more of an incentive (another assignment, perhaps) in the couple weeks between the working prototype deadline and the end of the semester. It's not a complete design iteration, but it is enough time to make several minor changes that can make a big difference. As of now, only personal motivation is there to drive these addition made to the prototype.

Given more time and money, what upgrades could be made to the working prototype?

There are several upgrades we would like to make if given more time. To decrease the weight, wood would not be the primary material, the rollers could decrease in size and density, and the length could be decreased. For better portability we would add snaps to secure the two halves of the running deck together, a handle to carry it with, improve the hinge design, and have foldable or removable legs. We would also add rubber dampers/stoppers to the bottom of the legs to help dissipate impact energy and minimize slipping between the legs and the floor.

8.3 Team Organization

Were team members skills complementary? Are there additional skills that would have benefitted this project?

Our skills were generally complementary to one another. We did not require significant use of the machine shop or other tools that any of us were relatively unfamiliar with, it was generally just the use of various saws and drills. The three of us had a different enough way of approaching problems we faced that we never felt we could not solve an issue or were stuck to choose a poor solution.

Does this design experience inspire your group to attempt other design projects? If so, what type of projects?

Yes, our group enjoyed the challenge of designing. Though we do not have specific projects in mind, it was very nice to finally have a class where we could build things with our hands and solve problems on a physical system as opposed to just theoretical answers with pencil and paper. Solving issues that others can't or don't have the time/resources to is what drew us to be engineers in the first place.

Appendix A Cost Accounting Worksheet

The actual cost of parts purchased are shown in Table A1. Many items changed between our initial list of parts and our actual parts used. This greatly reduced our initial cost and the chosen materials were easy to work with.

Table A1: Cost of equipment purchased for the prototype construction.

	Part	**Source**	**Part Number**	**Description**	**Unit Price**	**Quantity**	**Total Price**
1	Red Oak Board	Menards	1043914	2"x2"-8'	$18.83	1	$18.83
2	PVC Piping	Menards	6898588	4"x5'	$9.73	1	$9.73
3	PVC Cap	Menards	6891996	4"	$5.78	4	$23.12
4	Hinges	Menards	2268024	3.5", 5/8" kn, 3 Pack	$7.48	2	$14.96
5	Mending Brace	Menards	2256104	2"x1/2", 2 pack	$0.62	1	$0.62
6	Steel Rod	Home Depot	887480004878	36"x1"x16Ga	$13.67	2	$27.34
7	MDF Board	Home Depot	99167223032	3/4" 2'x4'	$13.06	1	$13.06
8	Conduit Hangers	Home Depot	785991105122	3/4", 3 pack	$1.84	2	$3.68
Total							**$111.34**

Appendix B   Final Design Documentation

To show various features of the treadmill in more detail, a total of four drawings were created. Figures B1 - B4 show a half of the running deck with the hinge slots cut out, the hinges used to connect the two halves of the running deck, a roller the belt rotates around, and a bracket connecting the running deck to the roller axle, respectively

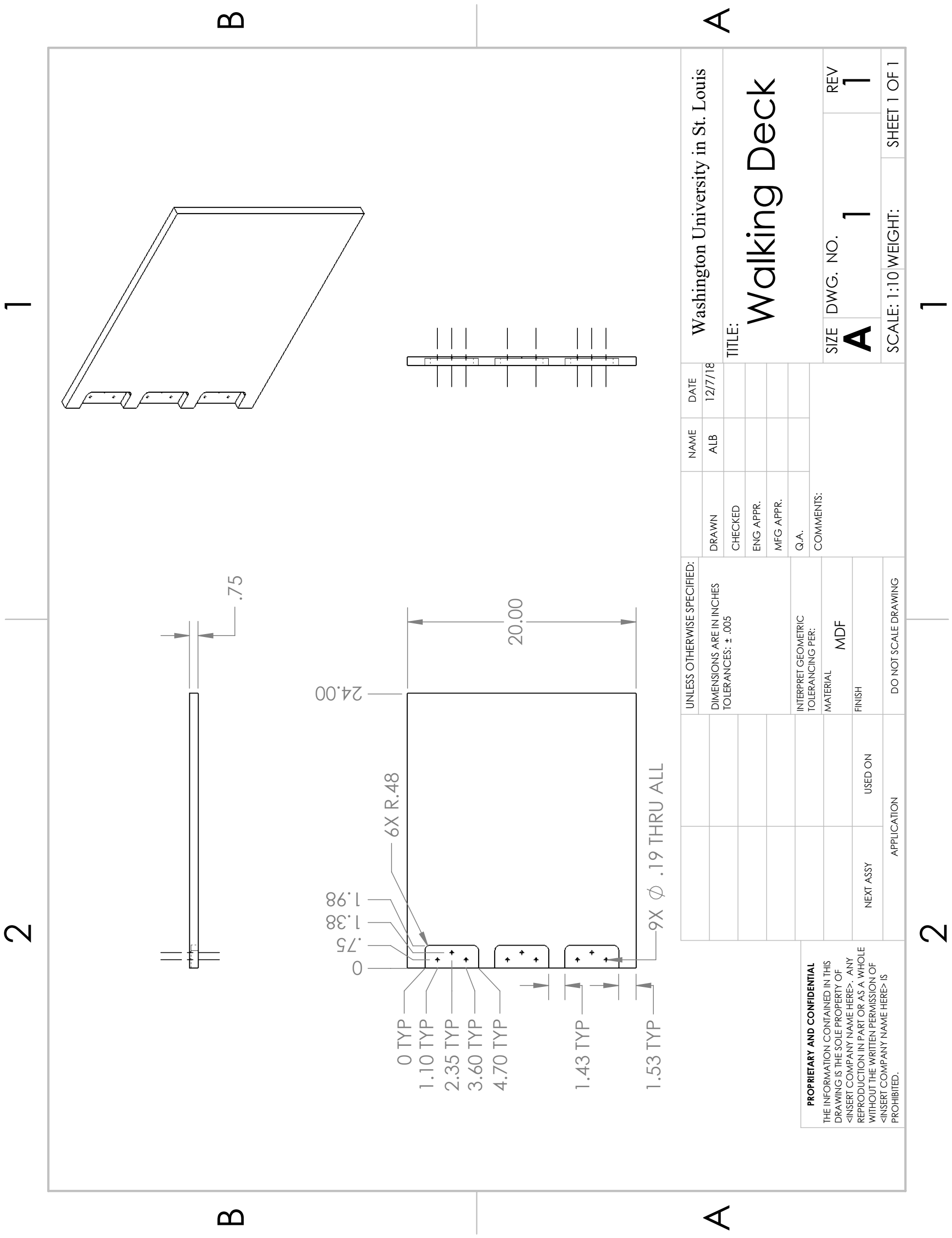


Figure B1: Running deck half including hinge cut outs.

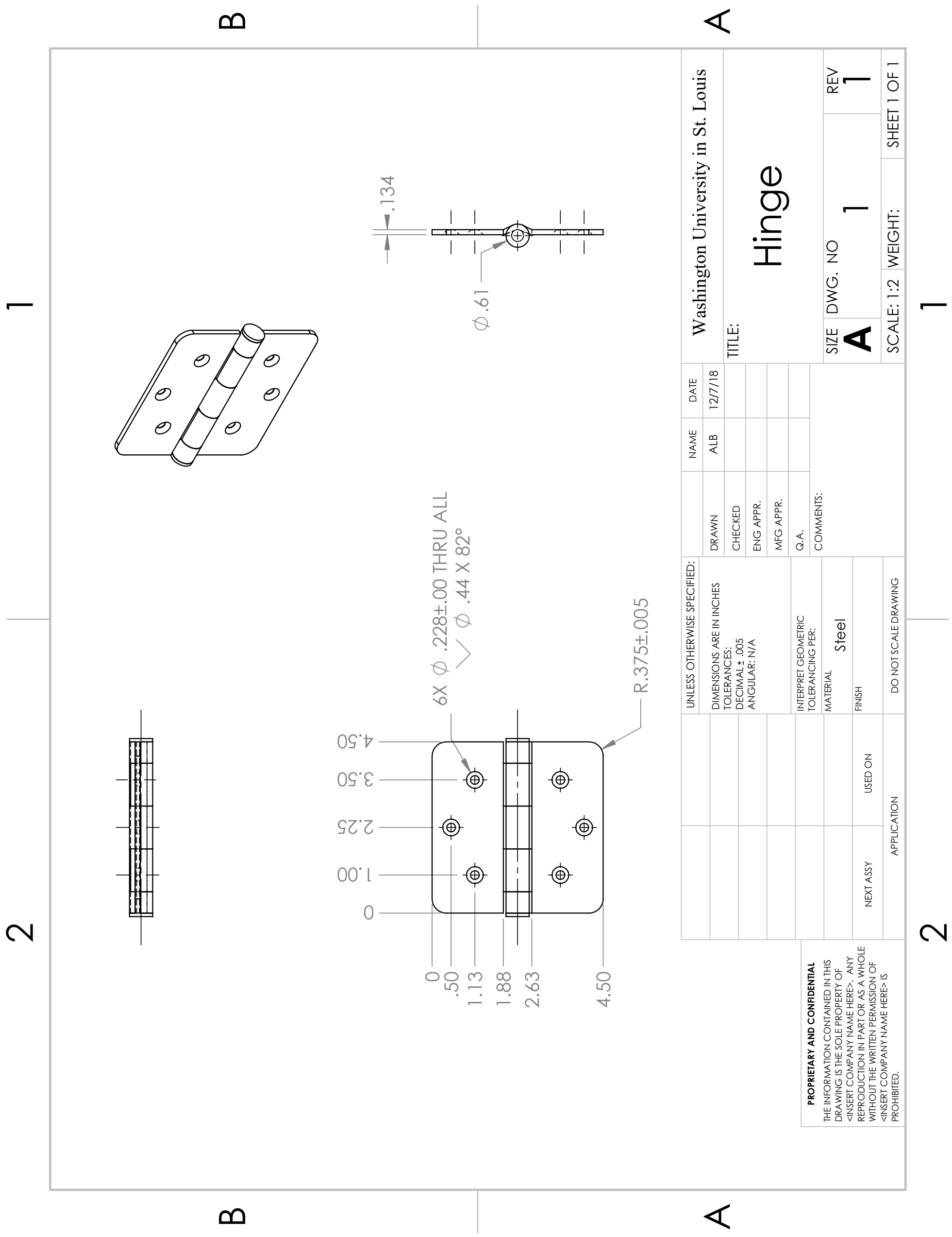


Figure B2: Hinges attaching two halves of the running deck.

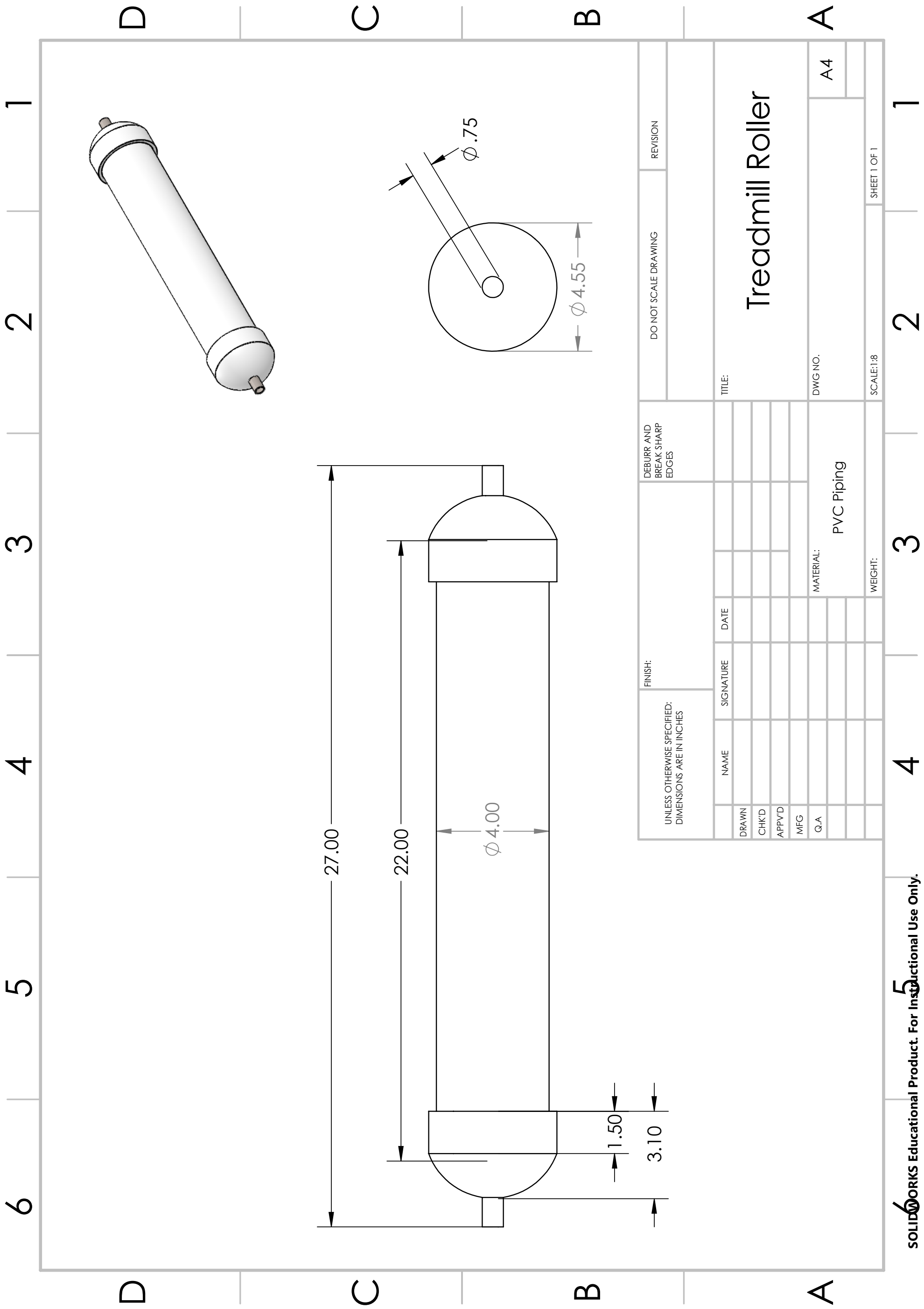


Figure B3: Roller and axle.

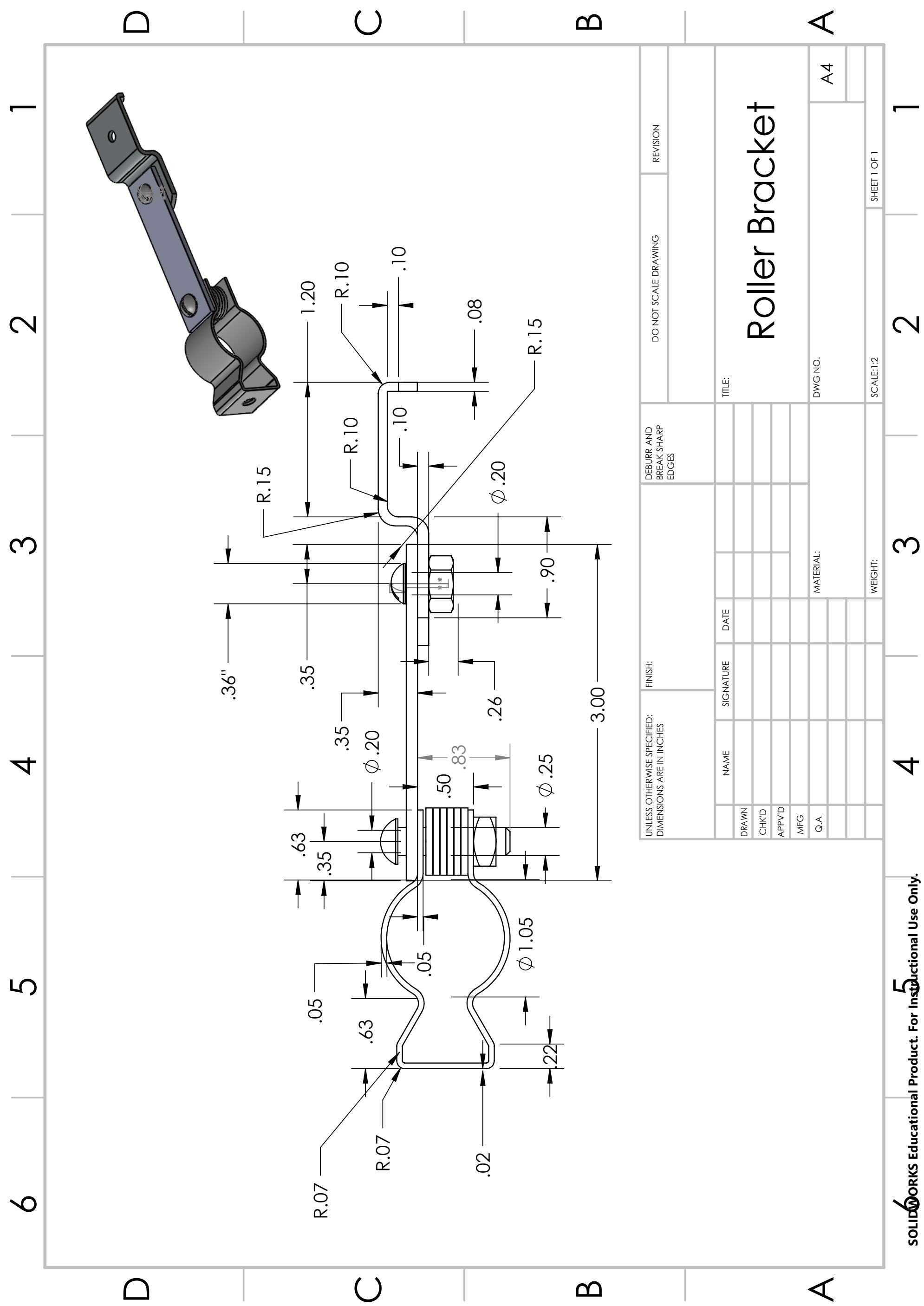


Figure B4: Bracket connecting running deck and roller.

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